

**ASSESSMENT OF FARMER-LED IRRIGATION DEVELOPMENT (FLID) IN SOUTH AFRICA:
A CASE STUDY OF VHEMBE DISTRICT**

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ABSTRACT

Small-scale farming has been identified as a driver of poverty reduction and food security worldwide. However, several issues facing small-scale agriculture are exacerbated by factors such as water scarcity, soil degradation, and climate change. In sub-Saharan Africa, Farmer-led irrigation development (FLID) has emerged as a decentralised pathway for agricultural intensification, particularly in semi-arid regions. Despite its growing popularity and relevance worldwide, farmer-led irrigation development in South Africa remains insufficiently quantified, particularly with respect to its performance determinants and environmental sustainability. Hence, identifying, characterising, and assessing FLID, along with the associated agricultural water and soil management practices, will improve the country's agricultural sector. In this context, this study assessed FLID in South Africa, integrating socio-economic analysis with empirical soil and irrigation water assessments to evaluate farm productivity outcomes, irrigation water quality impacts, and soil sustainability under independent smallholder farms.

A mixed-methods design was employed. Structured questionnaires were administered to 66 irrigation farmers across Thulamela and Makhado municipalities to characterise irrigation technologies, water sources, cropping intensity, soil–water management practices, institutional linkages, and income performance. Principal Component Analysis (PCA) identified composite management dimensions, and Multiple Linear Regression (MLR) quantified their influence on farm income. From this survey, eight representative farms were purposively selected for detailed biophysical assessment. Soil samples were collected from cultivated and adjacent uncultivated reference areas at depths of 0–20 cm and 20–40 cm. Undisturbed cores were used to determine bulk density (BD), porosity, and soil water retention curves (SWRC), amongst others, while composite samples were analysed for pH, electrical conductivity (EC), exchangeable bases, sodium adsorption ratio (SAR), nitrate nitrogen, available phosphorus (P), and potassium (K). Irrigation water samples were analysed for EC, SAR, major cations, and nitrate. Statistical analyses included analysis of variance, descriptive statistics, correlation, and regression at $p \leq 0.05$ using Minitab version 19.0. for soil and water data, while the Statistical Package for Social Science (SPSS) was used to analyse the questionnaire data.

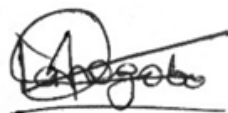
Results show that 63% of farmers relied on boreholes and 62% used drip irrigation, enabling two to three cropping cycles annually. Income performance was significantly associated with integrated soil and water-saving knowledge and irrigation scheduling capacity ($P \leq 0.05$), indicating that management intensity rather than farm size determined productivity. However,

groundwater dependence introduced measurable chemical risks. Borehole water exhibited a mean electrical conductivity of 737 $\mu\text{S}/\text{cm}$ and SAR of 1.09, with 75% of samples exceeding FAO salinity risk thresholds. Irrigation water electrical conductivity was positively correlated with soil sodium adsorption ratio at 0–20 cm ($r = 0.753$, $p = 0.015$), while irrigation water sodium adsorption ratio explained 59.81% of the variability in surface soil nitrate nitrogen ($R^2 = 0.598$, $p = 0.024$), demonstrating a statistically significant soil response to irrigation water quality. Concurrently, cultivated soils showed substantial nutrient enrichment relative to reference sites, with available phosphorus increasing by 309%, nitrate nitrogen by 435%, and exchangeable potassium by 73% ($P \leq 0.05$), reflecting active fertilisation practices. Mean bulk density was $1.36 \text{ g}/\text{cm}^3$, and soil water retention curve analysis revealed a mean available water capacity of $0.24 \text{ m}^3/\text{m}^3$, ranging from $0.17 \text{ m}^3/\text{m}^3$ in sandy soils to $0.30 \text{ m}^3/\text{m}^3$ in clay soils. Soil water retention curve (SWRC) analysis revealed a mean available water capacity of $0.24 \text{ m}^3/\text{m}^3$, ranging from $0.17 \text{ m}^3/\text{m}^3$ in loamy sands to $0.30 \text{ m}^3/\text{m}^3$ in clay soils. The greater buffering capacity of clay-rich soils moderated sodium accumulation and moisture stress, highlighting the role of pedological variability in system resilience. Although no severe degradation thresholds were exceeded, the statistically significant soil–water interactions indicate detectable early-stage sodicity development. FLID in Vhembe District, therefore, represents a productive yet environmentally conditional intensification pathway, where long-term sustainability depends on proactive groundwater monitoring, improved soil management, and stronger institutional integration to safeguard soil functionality and smallholder livelihoods in semi-arid South Africa.

Keywords: Farmer-led irrigation development, agricultural water management, soil physicochemical properties, irrigation water quality, soil water retention curve.

DECLARATION

I, **Natalian Madikelele Mamogobo (19018535)**, hereby declare that this research dissertation for the Master of Science in Agriculture in Soil Science at the University of Venda is my original document and has not been submitted for any degree at any other university or institution. I further declare that this dissertation does not contain any material from other sources, except where such material has been properly acknowledged and referenced in accordance with accepted academic conventions.



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Date..... 23/02/2026

As the candidate's main supervisor/co-supervisor, I agree to the submission of this dissertation as the student's original work:



Signed:

(Candidate's Supervisor: Prof. J.J.O. Odhiambo)

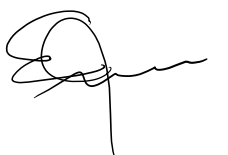
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Date..... 23/02/2026

PUBLICATIONS AND CONFERENCE PRESENTATION

This section outlines the sections of this dissertation that were presented at a conference. The research, analysis, results, and presentation reported are based on data collected from various FLID farmers, which have been compiled to yield the study's overall findings. All these chapters and the conference or symposium presentation were prepared by Mr. NM Mamogobo as the corresponding author (*), under the supervision, guidance, and review of my supervisors, Prof. JJO Odhiambo, Dr. FCM Onyando, and Dr. EM Mwendera.

Mamogobo, N.M.*, Odhiambo, J.J.O., Muga, F.C., & Mwendera, E.M. (2025). Effect of Farmer-Led Irrigation Practices and Water Quality on Soil Physicochemical and Hydraulic Properties. Oral presentation delivered at the 7th Annual International Engineering Conference (EC2025), University of Nairobi, Nairobi, Kenya, 21–25 October 2025.

Mamogobo, N.M.*, Odhiambo, J.J.O., Muga, F.C., & Mwendera, E.M. (2024). Characterization of farmer-led irrigation development (FLID) and associated agricultural water management (AWM) practices in Vhembe District. Oral presentation presented at the SAIAE and PASAE International Symposium, Cape Town, South Africa, 23–25 October 2024.

DEDICATION

I dedicate this dissertation to the Lord Almighty God and my family, who provided me with light in my darkest days, courage, wisdom, and strength to pursue my ambitions. I also dedicate this work to my supervisors and everyone who contributed to its success, whose unwavering love, support, and sacrifices made this journey possible. Your encouragement gave me strength during challenging moments and the motivation to persevere. I am forever grateful.

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ABBREVIATIONS AND ACRONYMS

FLID	=	Farmer-led Irrigation Development
FLI	=	Farmer-led Irrigation
AWM	=	Agricultural Water Management
FAO	=	Food and Agriculture Organization
SSA	=	Sub-Sahara Africa
SPSS	=	Statistical Package for Social Sciences
MLR	=	Multiple Linear Regression
PCA	=	Principle Component Analysis
IDAWM	=	Irrigation Development and Agricultural Water Management
IWMI	=	International Water Management Institute
NPD	=	National Planning Commission
DWS	=	Department of Water and Sanitation
SIS	=	Small Irrigation Schemes
NGO	=	Non-Governmental Organization
ARC	=	Agriculture Research Council
WRC	=	Water Research Commission
CPR	=	Common Pool Resources
IMT	=	Irrigation Management Transfer
DARLD	=	Limpopo Department of Agriculture
ARDC	=	Agriculture and Rural Development Corporation
WUA	=	Water Users Association
RESIS	=	Revitalization of Small Irrigation Schemes

IMC	=	Irrigation Management Committees
HDI	=	Human Development Index
VDM	=	Vhembe District Municipality
AS	=	Aggregate Stability
AWC	=	Available Water Capacity ($\text{m}^3 \text{ m}^{-3}$)
BD	=	Bulk Density (g cm^{-3})
Ca	=	Calcium (mg L^{-1} or mg kg^{-1})
CEC	=	Cation Exchange Capacity ($\text{cmol}(+) \text{ kg}^{-1}$)
CV	=	Coefficient of Variation (%)
SD	=	Standard Deviation
EC	=	Electrical Conductivity ($\mu\text{S cm}^{-1}$)
K	=	Exchangeable Potassium (mg kg^{-1})
LU	=	Land Use (C=Cultivated, F=Fallow)
SD	=	Sampling Depth (0-20 cm, 20-40 cm)
Na	=	Exchangeable Sodium (mg kg^{-1})
OC	=	Organic Carbon (%)
P	=	Phosphorus (mg kg^{-1})
SAR	=	Sodium Adsorption Ratio
SWRC	=	Soil Water Retention Curve

CHAPTER ONE: INTRODUCTION

This chapter presents the general introduction, problem statement, study justification, objectives, and research hypotheses.

1.0. General Introduction

Agriculture is an important economic activity globally, particularly in South Africa, where it can reduce poverty through the creation of employment (Cai et al., 2017, Oni et al., 2012). However, agriculture uses over 70% of the world's fresh water resources, thereby making water security crucial to the agricultural sector (Taylor, 2015). Sub-Saharan Africa continues to witness significant population growth, leading to increased water use (Hajer et al., 2016). Furthermore, increasing population growth will result in high food and nutritional insecurity and food import bills for the African continent (Denison, 2020). Governments and farmers worldwide are facing new difficulties relating to water quality and quantity due to the influence of climate change, pollution, and competition for water among sectors (Denison, 2020). Sinyolo et al. (2014) Stated that the increasing scarcity of water in South Africa and competition from other economic sectors put the irrigation capacity of farmers under tremendous pressure. Therefore, sustainable management of water resources and the expansion of agricultural growth are critical to ensure food security (Taylor, 2015).

The agricultural landscape in Africa is dominated by small-scale farmers who rely heavily on rainfall, with limited irrigation (Denison, 2020). Smallholder farmers, particularly those who practice rain-fed agriculture, frequently experience water shortages and struggle to increase and sustain their agricultural production (Tamburino et al., 2020). Consequently, irrigated agriculture has been proposed as an ideal supplement to rain-fed agriculture to ensure food security, particularly in regions with low rainfall (Chidavaenzi et al., 2021).

Irrigated agriculture can produce double the yield per unit of land area compared to rainfed agriculture (World Bank, 2020). However, water insecurity is the primary problem with irrigated agriculture in Africa, particularly in South Africa. The African Development Agenda 2063 advocates for additional interventions to further irrigation development and sustainable Agricultural Water Management (AWM) (Denison, 2020). The International Water Management Institute (IWMI) anticipates that by 2025, an additional 29% of irrigated land will be needed to sustain food production and reduce poverty on the African continent (Rijsberman, 2006). Enhancing Irrigation Development and Agricultural Water Management (IDAWM) practices and

providing the agricultural sector with reliable access to sufficient high-quality water are the primary objectives of the African continent (Denison, 2020). As a result, there is tremendous pressure on agriculture, especially the irrigation industry, to ensure food security for Africa.

Most public irrigation schemes in Africa were developed through government and donor-funded projects to improve agricultural productivity, enhance rural economic development, and eradicate poverty (Machethe et al., 2004). The transfer of administration of such irrigation schemes to local communities and non-governmental organizations (NGOs) has predominantly led to their failure due to a lack of organizational capacity, inadequate support, and unsuitable land tenure systems (Machethe et al., 2004). For instance, the irrigation management transfer (IMT) initiated by the South African government to hand over the control of small-scale irrigation schemes to NGOs and black farmers resulted in the collapse of most of the irrigation schemes targeted (Machethe et al., 2004). Subsequent government investment through the revitalization of smallholder irrigation schemes (RESIS) has also been unsuccessful since a majority of the schemes had collapsed or were malfunctioning due to economic and infrastructural issues (Gomo, 2012, Muluki et al., 2022, Phali et al., 2022).

Despite the documented failures of the government and the donor-funded Small-scale Irrigation Schemes (SIS), there is increasing expansion of irrigated agriculture in Africa through farmer-led initiatives (Cousins, 2013). The farmer-led irrigation development (FLID) is a recent phenomenon that can be defined as a process where farmers alone or as a group, take responsibility for improving their water use for agriculture by taking the lead in the establishment, improvements, and introducing changes in market linkages, knowledge production, investment patterns, the governance of land and water, and technology use (Lankford, 2009, Wiggins and Lankford, 2019, Woodhouse et al., 2017). The FLID is one of four pathways proposed by the African Union Framework for IDAWM to boost agricultural sector growth and development (Denison, 2020). These four pathways include: Pathway 1, Improved water control and watershed management in rain-fed farming; Pathway 2, Farmer-led irrigation development; Pathway 3, Irrigation scheme development and modernization; and Pathway 4, Unconventional water uses for irrigation. The FLID is significantly gaining prominence in Africa as a vital variable facilitating agricultural water expansion (Lankford, 2009). Furthermore, FLID serves as a catalyst for change, raising incomes and ensuring food security.

The South African Agricultural sector is dominated by a small number of large-scale commercial farmers who produce most of the agricultural output, and by millions of resource-constrained small-scale farmers who contribute very little to total national agricultural production. The SIS accounts for 3% of the irrigated area in South Africa and is essential to rural economic empowerment because of their location in rural areas (Denison, 2020, Maepa et al., 2014, Sinyolo et al., 2014). A large proportion of the small-scale farmers in South Africa are found in Limpopo province, and coupled with a high percentage of the rural population, makes Limpopo province ideal for the implementation of the FLID pathway (Oni et al., 2012).

Sustainable and consistent crop production among small-scale farmers is possible through the improvement of FLID and proper agricultural water management practices (Patle et al., 2020). However, extensive information on AWM practices and irrigated-equipped locations is limited due to undocumented information on farmer-led irrigation development in Africa (Denison, 2020). Therefore, it is crucial to characterize the various types of FLID practices in South Africa, particularly in the Limpopo province, to understand their status, types, scales, and performance.

1.1. Problem statement

South Africa is a water-scarce country, which makes water a limiting factor in agricultural growth and development (Adewumi et al., 2010, Oni et al., 2012, Todorovic et al., 2015). Improper agricultural water and soil management practices, coupled with water scarcity and climate variability, lead to reduced agricultural production and declining soil fertility, thereby threatening food security for the growing human and livestock populations. In addition, inadequate soil fertility is one of the principal and pervasive constraints on crop production for most farmers in South Africa, due to soil degradation and erosion that destroy topsoil and essential nutrients. The deployment of AWM practices and farmer-led irrigation to propel agricultural growth in the country falls short of the potential. This is due to undocumented information on Farmer-led Irrigation in the African continent, including South Africa (Denison, 2020). As a result, there is an urgent need to document FLID nationwide, as it is an essential factor in supporting agricultural water development.

1.2. Justification of the study

Agriculture consumes 60% of South Africa's water resources, and the International Water Management Institute (IWMI) predicts 29% more irrigated land will be needed by 2025, further straining water resources (DWAF, 2021). Despite the increasing threat of water shortages in agriculture, information on AWM practices and irrigated-equipped locations remains outdated due to a lack of documented information on FLID and its interactions globally, especially in South Africa. There is a need to understand the extent and magnitude of FLID, as well as its successes and challenges. The successful assessment of FLID by identifying, characterizing, and evaluating its effects on soil physicochemical properties and crop performance could improve irrigation development, food security, and ultimately increase production. Furthermore, the study will broaden knowledge of FLID and AWM, providing recommendations and a deeper understanding of how FLID can be improved to enhance farmers' livelihoods.

The current study aims to inform policy formulators and institutions, such as the Departments of Agriculture, Land Reform, and Rural Development, and the Department of Water and Sanitation, in South Africa, particularly Limpopo Province and the Vhembe District. The results of this study will also pave the way for future researchers to implement effective agricultural water and soil management practices and document irrigation technologies suitable for Limpopo province, utilizing the available information.

1.3. Objectives of the study

1.3.1. Broad objective of the study

The broad objective of the study is to assess the FLID in South Africa.

1.3.2. Specific objective of the study

The specific objectives are:

- i. To identify and characterize the farmer-led irrigation practices in the Vhembe district.
- ii. To assess the factors that influence the performance of farmer-led irrigation.
- iii. To determine the effect of farmer-led irrigation practices and water quality on selected soil properties

1.4. Hypotheses

The hypotheses of the study include:

- i. There is significant differences in the characteristics of farms that practice farmer-led irrigation (FLI) in the Vhembe district.
- ii. There are significant differences in the factors influencing the performance of farmer-led irrigation.
- iii. Farmer-led irrigation practices and water quality have a significant effect on selected soil physical and chemical properties.

1.5. Dissertation Outline

This dissertation consists of seven chapters.

Chapter One	Contains a brief introduction of the study, a problem statement, a justification of the study, research objectives, and hypotheses.
Chapter Two	This chapter presents the literature review relevant to the study. Furthermore, this chapter discusses Farmer-Led Irrigation Development (FLID) in global and South African contexts, identifying the opportunities and challenges associated with FLID.
Chapter Three	Presents the characteristics and performance determinants of farmer-led irrigation development and the associated agricultural soil and water management practices.
Chapter Four	Presents the effect of Farmer-led Irrigation practices and water quality on selected Soil Physical and Chemical Properties.
Chapter Five	Presents the summary of the study, discusses the significant conclusions, and provides recommendations arising from the study.

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CHAPTER TWO: LITERATURE REVIEW

This section reviews specific aspects of FLID and AWM practices globally and in South Africa. In addition, the section examines methods for characterizing FLID and AWM.

2.1. Overview of irrigation development in Sub-Saharan Africa

Irrigation development refers to the designing, planning, implementation, and management of irrigation systems to support the agricultural sector (Mati, 2023). Irrigation is a key factor in improving agricultural productivity to mitigate poverty and provide food to an expanding population (Dirwai, 2019). Furthermore, it is an essential pathway for small-scale farmers to fortify their resistance to climate change. This is achieved by providing reliable access to sufficient water for the crops through artificial applications that can be closely monitored and regulated, such as pipes and canals (Abioye et al., 2020). Irrigation has the potential to increase yields of most crops by between 100 and 400%, and it is expected that 70% of all grain will be produced from the world's irrigable land by the year 2046 (Rockström et al., 2009). Twenty percent of the cultivated area globally is under irrigated agriculture, accounting for forty percent of all food produced globally (World Bank, 2022).

Irrigation enables farmers to cultivate crops in areas previously considered unsuitable for farming due to insufficient, unpredictable, and unreliable rainfall (Nkiaka et al., 2021). However, irrigation potential is unexploited in many African nations. Large-scale irrigation initiatives that followed independence in sub-Saharan Africa largely failed to deliver the promised benefits of expanding irrigated regions or promoting better economic development and food security (Higginbottom et al., 2021). Individual irrigation schemes may function poorly due to governance issues, build-decay-refurbish cycles, high development costs, poor management, a lack of rural finance, and the expense of fertilizer (Harmon et al., 2023, Higginbottom et al., 2021, Redicker et al., 2022). According to estimates by De Bont (2018), 40% of all African agricultural land is occupied by 80% of farms with less than two hectares. The proportion of small-scale irrigation as a percentage of the established irrigation varies across Africa, ranging from 3% in South Africa to 80% in Tanzania (Backeberg and Sanewe, 2010, Van Averbeké et al., 2011a).

Irrigation in SSA once reached a point where it was failing; for example, the failures of small-scale irrigation that were offered to farmers in Malawi were failing due to expensive fuel and maintenance expenses (Kamwamba-Mtethiwa et al., 2021). However, in the late 2000s, government investment in irrigation in Sub-Saharan Africa (SSA) resumed after a 20-year hiatus

(Turral et al., 2010). Recent research has focused on investigating the potential and limitations of irrigation development in SSA by seeking desirable investments for the SSA context (Fujjie et al., 2011, Woodhouse et al., 2017, Xie et al., 2014, You et al., 2011). Funders from bilateral agreements and other international organizations have shown focused attention on irrigation and agricultural water management at large (Giordano et al., 2012; Woodhouse et al., 2001). If poorly managed, irrigation agriculture can lead to environmental degradation, soil salinization, and water scarcity. Therefore, effective irrigation management is crucial to ensuring the long-term viability of irrigated agriculture. Water plays a vital role in the agricultural production sector and remains a critical resource for both manufacturable and consumable-based activities that support various livelihoods (Samian et al., 2015). Competition for water resources is expected to increase, affecting the agricultural sector. Therefore, protecting and managing water resources is essential to improving food security (DWA, 2013).

2.2. Irrigated agricultural production in South Africa.

Agricultural production is an essential sector of the South African economy, contributing to food security and economic growth. Agricultural production accounts for around 2.53 % of the country's GDP and employs approximately 7% of the population (Cai et al., 2017). The country has a diverse agricultural sector, with a range of crops and livestock. The majority of South Africa's Agroecological regions (60%) receive less than 500mm of rainfall per annum, and only 10% receive 750mm, which results in limitations of the country's agricultural production (Cousins, 2013). Consequently, irrigated farming is necessary to increase agricultural production.

South Africa is one of the few African nations with well-developed water resources and irrigation infrastructure. Approximately 83% of the land that may be used for irrigation in South Africa has already been developed (Maepa et al., 2014, Van Averbeké et al., 2011b). Research has shown that irrigated agriculture is the biggest water consumer in South Africa (Blignaut et al., 2009; Velasco-Muñoz et al., 2019). Nearly 30% of all crops are produced through irrigated agriculture, which also uses the most water nationwide (Fanadzo, 2012). South Africa is a water-stressed country with an unsustainable water consumption path (Adewumi et al., 2010). There are many challenges stemming from irrigation water management at the farm that necessitate implementing water management policies to mitigate or limit agricultural water demand (Sun and Fu, 2016). Denison (2020) argues that adopting irrigation and water management practices will address water scarcity issues and increase the productivity of agricultural resources.

South Africa ranks as the 30th driest nation in the world in terms of water availability per capita and receives approximately half of the average annual global rainfall (Fanadzo and Ncube, 2018, Schreiner et al., 2010). Nonetheless, according to Hartley et al. (2021) South Africa's crop production is dominated by rain-fed agriculture, and irrigated crops account for only about 20% of total crop yield. Fujiie et al. (2011) Reported that small-scale irrigation is a crucial element of agricultural development to boost food crop production, household incomes, food security, and support livelihoods across numerous SSA nations. Small-scale irrigation is often characterized by the use of less formal, basic technologies that rely on manual labour. Irrigation can be categorized by water consumption (large or small users) and by type, such as full-control irrigation, supplemental irrigation, and other scales of water use. Understanding these scales is essential for water allocation and supply, which are core components of irrigation development and management. This is due to the rapid growth in both water use and users.

The National Water and Sanitation Master Plan stated that South Africa will require 17% more water in 2030 than is currently available (Department of Water and Sanitation, 2018). The International Water Institute (IWMI) estimates that approximately 29% more irrigated land will be required by 2025 to mitigate poverty and sustain food production in Africa (IWMI, 2016). The main problem with irrigated areas, which already contribute to about 70% of water withdrawals in South Africa, is that the demand for water is surpassing the supply because surface water in most catchments is entirely or even excessively allocated (Mabhaudhi et al., 2018, Seeliger et al., 2018). Hence, irrigation continues to face pressure on water supply due to increasing demands from other users.

2.3. Small-scale irrigated agriculture in South Africa.

The National Development Plan of South Africa identified small-scale farming as a sector that can improve the rural economy through increased irrigated agriculture in rural areas (DAFF, 2015; Cousins, 2013). Additionally, the National Development Plan estimated that the agricultural sector could create approximately 1 million new jobs by 2030 by expanding irrigated agriculture from 1.5 million hectares to 2 million hectares, among other factors (Department of Agriculture, Forestry and Fisheries, 2015). The government of South Africa identified smallholder farming as one of the best vehicles to mitigate poverty and achieve rural development (Machethe, 2004, Pienaar and Traub, 2015). The small-scale farmers in South Africa are primarily black, mostly

living in their former homelands. However, it should be recognized that small-scale farmers are not a homogeneous group, nor are all black farmers small-scale farmers (Machethe et al., 2004).

Various analysts utilize different criteria to categorize farmers as small-scale, but the primary ones are the size of the farm, the goal of the production (commercial or survival), the income level, and, in the case of South Africa, the race of the farmer (Fanadzo, 2012). The small-scale farmers can be categorized into four groups, namely: independent irrigation farmers, farmers on irrigation schemes, community gardeners, and home gardeners (Crosby et al., 2000, De Lange, 1994, Du Plessis et al., 2002, Van Averbek, 2008). Furthermore, small-scale irrigation can be further categorized into formal and informal irrigation systems. Formal irrigation systems are public or private initiatives that were created under governmental institutions and whose characteristics have been documented in national statistics (Gutiérrez-Malaxechebarria, 2013). The management of the water supply to crops in small-scale irrigation farms is started, arranged, and controlled by the landowners (Adams and Carter, 1987). These activities are limited to 10 ha per household, and sometimes as little as 0.1 ha. South Africa has approximately 1.3 million ha of irrigated land, of which approximately 0.1 million ha is owned by small-scale farmers (Backeberg, 2006, Fanadzo, 2012, Fanadzo and Ncube, 2018, Van Averbek, 2008, Van Averbek and Mohamed, 2006). The expansion of irrigated agriculture is expected to be driven by independent irrigation farmers through farmer-led irrigation development initiatives (Cousins, 2013). Hence, contextualizing the Farmer-led Irrigation Development (FLID) as it is used in South Africa is necessary. Additionally, it is essential to comprehend the scope, difficulty, and accomplishments of FLID in South Africa.

2.4. Farmer-led irrigation development in a global perspective

According to Harmon et al. (2023) Farmer-led Irrigation development (FLID) has been used and described in different ways, including small, private, farmer-driven development of individual irrigation systems, small-scale private, and household irrigation. Most farms were privately owned and entirely under the farmer's control. They were typically smaller than 2 hectares, with the majority measuring about 0.1 hectares. The irrigation technologies were water-lifting (such as manual and motor pumps), water-harvesting, and water-saving technologies (Abric et al., 2011; Passarelli et al., 2018). Farmer-led irrigation (FLI) forms are diverse. Farmers typically use gravity

to extract water from lakes and rivers, but pumps are used when gravity isn't possible, and wells are dug to obtain surface water or groundwater aquifers (Wiggins and Lankford, 2019).

FLID can be defined as a process where farmers, alone or as a group, play a driving role in improving their water use for agriculture by taking the lead in the establishment, improvement, and bringing about changes in knowledge production, technology use, investment patterns, market linkages, and the governance of land and water (De Fraiture and Giordano, 2014, Harmon et al., 2023, Nkoka et al., 2014, Veldwisch et al., 2019, Wiggins and Lankford, 2019, Woodhouse et al., 2017). According to Lankford (2009) Most policymakers view farmer-led irrigation as ineffective and ignore it as spontaneous. However, Lankford (2009) identified FLID as the dominant process driving agricultural water expansion in Africa. Studies by the African Union, (2020), Mekonnen et al. (2022) and Minh et al. (2021) have shown the advantages of FLID, such as increased resilience to climate crises and improved food availability. Furthermore, an increasing number of sponsors and national governments view FLID as a type of climate-smart agriculture (CSA) (Harmon et al., 2023).

Farmer-led irrigation is a system initiated by farmers on their own. By definition, FLID emphasizes farmers' capacity to develop and improve irrigation systems. These farmers are mainly small-scale, informal farmers who aim to advance irrigated agriculture (Gutiérrez-Malaxechebarría, 2013). However, little is known about these farmers because they are challenging to find and identify among hundreds of satellite photos (Venot et al., 2021, Wiggins and Lankford, 2019). Furthermore, official reports and databases on African irrigated agriculture do not reflect irrigation initiatives initiated by farmers outside government-owned and managed irrigation systems (Venot et al., 2021). The technology and skills needed are less and beyond the reach of most researchers in SSA. Furthermore, the untraceable data on these farmers is due to continuous changes in water management practices outside conventional irrigation types and to a consensus that farmer-led initiatives are ineffective, inefficient, and incompatible with modern design.

According to De Fraiture (2014), Ghana reported 36,000 hectares of irrigation capacity in 2016. However, researchers estimate that 189,000 hectares may be irrigated, with most of the land used for private irrigation using motor pumps or buckets. Irrigated areas can be divided into four categories, according to FAO's AQUASTAT, which are: (1) complete control irrigation, (2) partial control irrigation, (3) irrigation through water harvesting, and (4) farming in flood recession zones and wetland areas (Venot, 2021). The first two categories are typically the focus of official government reports, while FLID, which is primarily informal, falls under the latter two categories

that are rarely recorded. The report from the FAO AQUASTAT survey of 2005 indicated that initiatives under local responsibility, controlled and administered by local people in response to their stated requirements, were not included in irrigated land (FAO, 2005; (Nkoka et al., 2014, Venot et al., 2021).

Furthermore, according to FAO data, the irrigated area in Sub-Saharan Africa (SSA) has grown by 56% since the early 1990s, compared with a 31% increase in arable crop areas. By 2014/16, 3.4% of arable land was irrigated, compared to 2.8% in 1990/92 (Wiggins and Lankford, 2019). Over 2 million hectares of irrigated area have been added by individual or small groups of farmers, with only a tiny part of this expansion coming from official irrigation schemes. Significant regions of FLID are often not included in official data in statistics. The rise of "small private irrigation" is a type of farmer-led irrigation development that has received increased attention recently in the literature on SSA (Burney et al., 2013, De Fraiture and Giordano, 2014). The international financial institutions and bilateral development organizations have begun to recognize the possibility of farmers managing their investments and establishing their water governance systems, thus spurring investment in FLID in SSA (Harmon et al., 2023).

The FLID is an alternative development to small-scale irrigation schemes where performance and sustainability concerns continue to prevail (Harrison, 2018). Research about farmer-led irrigation (FLI) practices in sub-Saharan Africa shows that the amount of irrigated land is significantly more than what official government evaluation reports have stated, leading to an over-use of water resources (Beekman et al., 2014, Woodhouse et al., 2017). According Duker et al. (2023b) Farmer-led irrigation is the foundation of farming families' livelihoods because it is recognized for its resilience and contribution to food security and economic development. Therefore, implementing the proper agricultural water management (AWM) practices in the irrigation sector provides a sustainable response to adapt to water shortages or improve the availability of water (Molobela and Sinha, 2011). According to Samian et al. (2015), to effectively manage the agricultural water, an increase in economic performance with reduced water and energy consumption is required. Studies have shown that the territories under AWM are likely much more significant than what is officially stated, and FLID has rapidly spread over the West, East, and Southern African regions (Cai et al., 2017, Denison, 2020).

2.5. Farmer-led irrigation development in South Africa

Farmer-led irrigation includes a varied range of farmers and farming techniques in various settings (Izzi et al., 2021, Woodhouse et al., 2017). Farmers take the initiative, making them more equipped to deal with and respond to context-specific difficulties and new opportunities, which leads to a dynamic yet non-linear form of smallholder irrigation (Hebinck et al., 2019). Available data has mostly focused on smallholder irrigation schemes (SIS), which account for 3% of the irrigated area in the South African region. The SISs are valued by the government because of their rural locations and ability to improve rural livelihoods (Chuchird et al., 2017, Sinyolo et al., 2014). The smallholder irrigation schemes (SISs) were constructed to meet the needs of small-scale farmers as a collective who cultivate small plots of land, exchange, and control a common pool of resources (CPRs) such as water and irrigation infrastructure (Dirwai, 2019, Machethe et al., 2004, Van Averbek et al., 2011b). However, most of the SIS, along with their water users, have continued to fail post-government withdrawal due to a mixture of technical and economic factors (Phali et al., 2022).

A significant number of smallholder farmers in South Africa are found in Limpopo province. It is one of South Africa's prime agricultural regions, often described as the "Garden of South Africa" (Cai et al., 2017). The province has different climatic regions, such as the Lowveld (arid and semi-arid) regions, the middle veld (semi-arid), the highveld, and the escarpment region (having a sub-humid climate with rainfall of over 500mm per annum (Cai et al., 2017, Dirwai, 2019, Oni et al., 2012). These distinct climates allow Limpopo province to produce various agricultural crops, including bananas, maize, wheat, tomatoes, and onions, under both rainfed and irrigated farming. The mapping based on remote sensing estimated 1.6 million hectares (Mha) in total to be cropland in the province, with only 262,000 ha irrigated in the 2015 winter season (Cai et al., 2017).

There are approximately 5,000 and 273,000 commercial and small-scale farmers, respectively, in Limpopo province (Statistics South Africa, 2002). The commercial farmers are primarily white, using the most advanced production technology and occupying the Transvaal portion of the Limpopo province, which covers 70% of the total land area in Limpopo province (Cai et al., 2017, Oni et al., 2012). At the same time, small-scale farmers are primarily located in the former homelands, which cover approximately 30% of Limpopo province's total land area. These farmers are characterized by small land sizes of approximately 1.5 hectares per farmer, poor infrastructure, and low levels of production technology. Most land-accessible smallholder farmers

are interested in commercial agriculture and view agriculture as an investment (De Bont et al., 2019b).

2.5.1. Characteristics of farmer-led irrigation in South Africa

The farmer-led irrigation (FLI) is defined by: (1) the farmer's entrepreneurial activity and risk-taking behavior; (2) the diverse range of irrigation technologies and farming systems; (3) capitalization that adheres to the commercial nature of reinvestments and logic into irrigation technologies and agricultural input; and (4) working together of farmers with various stakeholders along the value chain of agriculture (Kafle et al., 2022, Minh et al., 2021). The majority of irrigation investments made by farmers are funded informally by loans, savings, family, and friends, which is a sign of risk-taking behavior (Wiggins and Lankford, 2019).

The following traits are typically found in farmer-led irrigation operations (World Bank, 2021): 1. Growing high-value crops primarily for urban, peri-urban, and occasionally export markets. 2. Irrigates small fields of 0.5-2 ha on a small scale (<40 ha). 3. Consists of both individual and group schemes. 4. It is primarily self-funded and run by farmers. 5. Preferably uses several cropping. 6. Typically adopts crop firms that are focused on the market. 7. Use pumped systems (manual, small gasoline, or solar pumps) frequently but not always. 8. There is a high dependency on shallow wells using individual irrigation systems, water harvesting storage, or direct river pumping. 9. Horticultural or high-value crops are what farmers plant the most. 10. Family employment is used on smaller plots, while paid labour is used on larger farms.

FLI can further be categorized into two extremes: micro-irrigators, who water small plots for home consumption and local sale, and small-scale commercial irrigators, who water large plots intensively and sell much of their harvest for significant returns. Micro-irrigators contribute to low-income households, but do not significantly contribute to overall agricultural output (Wiggins and Lankford, 2019).

FLID comprises individuals and small organizations that fund the advancement of AWM and irrigation techniques. They are market-driven farmers primarily cultivating horticulture commodities. FLI is boosted by urban markets for higher-value produce, with newly irrigated areas producing fruit, vegetables, and fodder (Wiggins and Lankford, 2019). Vegetables (onions, pepper, tomato, cabbage, moringa, and others) make up the vast majority of irrigated crops, while cereals (rice, maize, and other grains) and fruit trees (lemon, mango, guava, grapefruit, and so on) make up a much smaller fraction (Soumaila, 2021).

The advantages of farmer-led irrigation systems include community development, local ownership, water management, resource control, and sustainability. Despite not being limited to a specific size range of farms, farmer-led irrigation development frequently involves farmers with less than 10 ha under cultivation, with most of them having less than 2 ha (Mati, 2023). Due to their limited resources (both financial and technical) and access to knowledge, small-scale projects are FLID's primary focus. Numerous typologies of FLID, primarily based on criteria such as farm size and crops grown, technological sophistication, labour organization, market orientation, and farming practices, provide evidence of this variability in farming (Hebinck et al., 2019, Izzi et al., 2021, Scoones et al., 2019). Furthermore, Farmer-led irrigation systems include furrow irrigation, bucket irrigation, tiny pumps, and partial water management in wetlands. Woodhouse et al. (2017) argue that access to the market is essential for the growth of FLID, as it is frequently involved in the production of high-value horticultural products.

2.5.2. Opportunities and drivers of farmer-led irrigation development

FLID has natural opportunities to expand irrigation agriculture's infrastructure, technologies, water supply, markets, and commercialization. In Africa, FLID has recently gained popularity and is recognized as a key factor driving the expansion of agricultural water use on the continent (African Union, 2020). Water availability on farms or nearby farmlands typically makes irrigation adoption easier, with or without outside assistance. As a result, FLID gives farmers the chance to invest in their own irrigation systems, which are straightforward and reasonably priced to use. FLID is comparatively sustainable due to the absence of excessive demands that impede decision-making in major public initiatives. FLID farmers are typically creative and willing to take chances through self-funded endeavours. They occasionally borrow money from other sources. They can overcome the difficulties associated with smallholder irrigation and boost the profitability of their crops by using funds from various sources to test new concepts and technologies (African Union, 2020).

The drivers of farmer-led irrigation development are linked to a highly adaptable informal sector that responds to the needs of small-scale farmers (Beekman, 2014). These links and contacts frequently arose from new settlers who moved into the area and had different backgrounds in irrigated agriculture or higher levels of education. This migration acts as a key conduit for disseminating knowledge and farming techniques that neighbouring farmers adopt (Beekman et

al., 2014). FLID attracts the attention of NGOs and other business sectors, both directly and indirectly. However, due to the lack of a survey of the significant FLID participants, it is unclear what is happening (Mati, 2023). FLID is driven by various factors, including the availability of land, water, and appropriate irrigation technologies; access to finance, credit, and investment opportunities; affordable irrigation equipment; easy access to markets; favorable farm-gate pricing of irrigated produce; and information and knowledge flows through various channels. These factors contribute to the economic returns of irrigated agriculture, allowing farmers to access resources like spares, fertilizers, seeds, and irrigation equipment (Mati, 2023, Beekman et al., 2014).

According to Woodhouse et al. (2017) and De Bont (2018) Farmers do not act alone or in isolation; instead, they operate within a broader network of state and non-state actors and adapt to changes in their socioeconomic environment through analysis of various farmers' irrigation efforts. According to Phakathi et al. (2021) Farmers can create unique, helpful, and legitimate institutional changes driven by them. While external actors like the government should direct, encourage, and regulate farmer-led schemes to ensure that the innovations deployed are socially and environmentally sustainable, farmer-led institutional innovations benefit improved scheme administration. Farmer-led innovations and initiatives focused on improving irrigation development based on existing data (de Bont et al., 2019a). The impacts of FLI vary, such as increased local employment.

2.5.3. Main challenges and constraints facing FLID

According to Mati (2023) in Kenya, farmer-led irrigation development's lack of acknowledgment of the policies and institutions in charge of irrigated agriculture is one of the biggest challenges it is currently experiencing. The first hurdle is persuading enough decision-makers or policymakers that FLI can support regional and local development in the manner that the research indicates it can (Wiggins and Lankford, 2019). This is because they are rare or unrecorded policy accomplishments with FLI (Wiggins and Lankford, 2019). Although FLID has been practiced for a long time and is not a novel concept, the sector has only recently received worldwide recognition (Mati, 2023, Woodhouse et al., 2017). In South Africa, information about FLID is not documented. Hence, it misses out on development support. Access to financial resources, technical expertise, institutional support, and governance, as well as the availability of markers and policies, rules, and regulations, are some of the difficulties that FLID faces (Izzi et al., 2021).

Another challenge small-scale farmers face is the inherently infertile nature of their soil (Hemming, 2016). In addition, high-quality seed, fertilizer, and crop protection chemicals are scarce. Marketing items are further complicated by poorly maintained roads, fluctuating market prices, and the inability to store production during low-cost periods. Comparable challenges can be linked to practitioners of FLI. However, reports of marketing challenges are less frequent since FLI is often only conducted when it is feasible to market output profitably (Wiggins and Lankford, 2019).

The policies hindering the performance of FLID in South Africa include, in communally managed irrigation schemes, the most common issues being water distribution and the proper management of common-pool resources (CPRs). According to policymakers, increasing the number of smallholder irrigation schemes (SIS) and revitalizing already existing or defunct ones can boost food production (Van Averbek et al., 2011b). But, the effectiveness of the SIS established as part of the post-apartheid land reform program has been dismal (Umhlaba, 2010; (Fanadzo and Ncube, 2018). Quantitative knowledge of water productivity and efficiency is limited, making it difficult for stakeholders to objectively assess different irrigation types. Physical problems reported from FLI include over-abstraction of water, particularly during dry seasons and droughts, causing well levels to fall (Wiggins and Lankford, 2019).

Lack of finance and institutional support

Access to financing remains a barrier preventing small-scale farmers in Africa from adopting modern irrigation systems and increasing their productivity and profitability (Khapayi & Celliers, 2016). The farmers are constrained by a lack of capital assets (machinery, irrigation equipment, and buildings) that would enable them to increase agricultural productivity, food security, and income (Karama et al., 2019). It is argued that a lack of finance might prevent farmers from timely access to equipment (Mdume et al., 2017). Therefore, most small-scale farmers in South Africa, particularly in rural irrigation schemes, rely on low-tech equipment and local tools such as hand hoes and machetes.

Access to irrigation water is unsatisfactory among smallholder farming communities (Sinyolo et al., 2014). The provision of support services remains a significant intervention in the agricultural sector for rural development, commercialization, food security, poverty alleviation, and income generation for smallholder farmers. In Limpopo province and elsewhere in South Africa, Irrigation schemes are generally limited to support services. Thus, it is difficult for schemes to cope when they encounter challenges such as financial constraints and animal damage.

Marketing facilities and poor infrastructure

Studies by Oparinde and Daramola (2014) and Raphela (2014) found that insufficient capital, high transportation costs, poor road network, poor storage facilities, lack of credit facilities, and inadequate farmer support services are among the factors that constrain small-scale farmers' access to markets. Limited access to agricultural technical aid and a lack of knowledge have previously been cited as affecting crop production. Since smallholder farmers often lack good roads, which can be used in delivering modern irrigation techniques to save water. It is frequently difficult for smallholder farmers to use modern irrigation technologies. However, smallholder farmers rely on traditional irrigation methods that are often ineffective, leading to water loss.

2.6. Agricultural Water Management (AWM) in South Africa (Limpopo).

Agricultural Water Management (AWM) is the process of managing water resources sustainably and efficiently without causing a negative impact on the environment and other water users for agricultural purposes and to maximize the ratio of crop water uptake to evaporation, runoff, and deep infiltration (Haacker et al., 2019, Smidt et al., 2016). The major goal of efficient agricultural water management is to boost economic performance while consuming less water and energy (Samian et al., 2015). As a result, AWM contributes to the achievement of the second Sustainable Development Goal (SDG #2), which seeks to eradicate hunger, guarantee food security, enhance nutrition, and support sustainable agriculture, which is a component of SDG #6 by sustaining and ensuring water availability (African Union, 2020). Water management involves the interaction between the engineering, human infrastructure, and the government (Kadyampakeni et al., 2014).

According to Molobela and Sinha (2011) and the African Union (2020), integrating agricultural water management (AWM) offers a sustainable way to adjust to water scarcity while maintaining operational capacity. Furthermore, in South Africa, particularly in Limpopo Province, agricultural production occurs largely under water-limited conditions characterized by erratic rainfall, high evapotranspiration, and recurrent droughts. These constraints necessitate irrigation as a critical input to stabilize crop yields and improve food security. Agricultural Water Management in South Africa operates within an Integrated Water Resources Management framework, in which water allocation, licensing, infrastructure development, and environmental protection are regulated at national and catchment levels (Denison, 2020).

The total area under Agricultural Water Management (AWM) in Africa is estimated to be 18.6 Mha⁻¹, including irrigation and other water-management technologies (Denison, 2020). However,

new evidence suggests that 18.6 Mha-1 is an underestimation, as farmer-led irrigation development covers a large area that is not officially recorded. This is evident because, beyond formal irrigation schemes, Farmer Led Irrigation Development has expanded rapidly, particularly in semi-arid districts such as Vhembe. In these systems, farmers independently invest in boreholes, pumps, and irrigation technologies. While this decentralised model improves access to water and supports multiple cropping cycles annually, it shifts responsibility for water abstraction, quality monitoring, and soil sustainability to the farmer.

The performance and sustainability of Agricultural Water Management under Farmer Led Irrigation Development therefore depend not only on water availability but also on water quality, irrigation method, soil characteristics, and on-farm management practices. Understanding these linkages is critical for assessing productivity outcomes and environmental implications in smallholder irrigation systems.

2.6.1. Water scarcity and quality

In SSA, water quality is a significant and escalating problem for water security (Chishugi et al., 2021). In many nations, anthropogenic activities such as mining significantly affect the quality of groundwater and surface water (Nkiaka et al., 2021). Poor water quality in SSA may be caused by several factors, including naturally occurring dangerous substances in the soil, such as nitrates and arsenic, Leaching of agricultural chemicals and fertilizers from agricultural fields, and industrial pollution from oil and gas (Adewumi and Laniyan, 2021, Bretzler et al., 2017, Curchod et al., 2020, Ouedraogo and Vanclooster, 2016). Due to nutrients from fertilizers, water quality is compromised. In community-managed schemes, there are differences in accessibility to water.

Water scarcity in Limpopo Province is driven by low and variable rainfall, prolonged dry seasons, and increasing competition between agricultural, domestic, and industrial sectors. Climate variability further intensifies water stress, increasing reliance on groundwater abstraction through boreholes. While groundwater provides a reliable source for irrigation, its chemical composition varies spatially and may pose salinity or sodicity risks (Rengasamy, 2010, Ayers and Westcot, 1985, Mohanavelu et al., 2021). Irrigation water quality is commonly assessed using electrical conductivity (EC), sodium adsorption ratio (SAR), pH, nitrate, and major cations. EC indicates total dissolved salts and reflects salinity hazard, while SAR measures the relative dominance of sodium over calcium and magnesium and indicates sodicity risk (Ayers and Westcot, 1985). High

salinity reduces plant water uptake through osmotic stress, while elevated sodium adsorption ratio promotes soil dispersion, reduces infiltration, and weakens soil structural stability (Ayers and Westcot, 1985, Rengasamy, 2010). Water quality deterioration in South Africa may result from natural geochemical processes, agricultural runoff, settlement discharge, dumping sites, livestock contamination, and industrial activities. However, in decentralised irrigation systems such as FLID systems, water abstraction is often carried out without routine chemical monitoring. Consequently, marginal water quality may gradually influence soil properties and crop performance without immediate detection in the long-term.

2.7. Soil and water management practices in FLID

Soil and water management practices determine how irrigation water interacts with the soil system. Farmers worldwide, both large- and small-scale, adopt various management strategies, including selecting irrigation systems, cropping systems, tillage practices, and fertilizer application. These farmers also include FLID practitioners, and these practices collectively influence soil physicochemical properties and overall irrigation performance. Soil is a non-renewable resource; therefore, it is crucial to continuously monitor its quality for sustainable land (Várallyay, 2007). South African small-scale farmers experience a decline in soil fertility, which is essential to crop production. The decrease in soil fertility is caused by soil erosion, which, over time, typically destroys the top fertile soil and essential nutrients, thereby affecting food production for most farmers.

Soil quality is essential in cropland development because soil requires substantial inputs of nitrogen (N), phosphorus (P), potassium (K), and organic carbon to achieve optimal crop yields by adding nutrients and improving fertility (Liu, 2012). In addition, the soil is affected by different agricultural practices such as cropping systems (e.g., Intercropping), organic and inorganic fertilizers such as NPK, irrigation technology (e.g., Drip or sprinkler irrigation), tillage practices (e.g., Conservation tillage), vegetative cover, type of water, and climatic conditions (Eyre, 2017). These management practices adopted by small-scale farmers affect sustainable agriculture and have a significant impact on the availability of soil chemical properties (such as C, N, P, K, Ca, and Mg) and soil physical properties, such as Bulk density and soil texture (Afzaal et al., 2020, Alotaibi and Kassem, 2021, Chartzoulakis and Bertaki, 2015, Du et al., 2015, Finley, 2016).

Furthermore, agricultural land-use practices have significant impacts on crop growth and yield, and major food production in Limpopo is carried out by small-scale farmers.

However, small-scale farmers' crop production is failing to meet the food requirements of the growing human population due to declining soil fertility (Chilonnda et al., 2007). Hence, water and soil nutrient management are critical to successful and sustainable agriculture. Irrigation management practices, soil management practices, agronomic management practices, and water laws and regulations are the four major categories into which sustainable agricultural water management methods can be divided (Finley, 2016). According to Myeni et al. (2021) Sustainable agricultural practices (SAPs) are therefore thought to be the most promising means of boosting the resilience and productivity of small-scale farming systems' agricultural production while safeguarding the planet's natural resources.

2.7.1. The effect of various irrigation systems on soil quality

The potential for expanding irrigated agriculture in Sub-Saharan Africa has been extensively discussed, along with its environmental impacts (Xie et al., 2023). Irrigation affects the environment in two ways: directly through water abstraction, which alters hydrological systems, and indirectly through the farming practices used on irrigated land. Potential consequences and issues include land and soil depletion, loss of agricultural biodiversity, poor soil quality, pollution from excessive fertilizer and chemical use, and loss of water to rivers and wetlands, which impacts fisheries, groundwater, and ecosystems. High irrigation water volumes can lead to nutrient leaching, altering soil pH and nutrient availability. Irrigation waters, whether derived from springs, diverted from streams, or pumped from wells, contain appreciable quantities of chemical substances in solution that may reduce crop yield and deteriorate soil fertility (Motsara, 2015). Hence, the quality and quantity of irrigation water, as well as irrigation technology, affect soil quality. The various irrigation systems include sprinkler, drip, and surface irrigation. According to Patle et al. (2020) most small-scale farmers in SSA employ surface irrigation techniques and disperse water through open channels.

Sprinkler

According to Ahmed et al. (2021), sprinkle irrigation is a method of applying irrigation water through showers resembling natural rainfall. Water is pumped through a pipe system and then sprayed onto the crops through rotating sprinkler heads. Generally, sprinkler irrigation is applicable to all types of crops. Water distribution across the field is uniform. Although applicable

to most soils, sprinklers are best suited to sandy soils with high infiltration rates. The sprinkler application rate must be set below the soil infiltration rate to avoid ponding and surface runoff. Therefore, avoiding poor soil quality such as affecting aggregate stability and bulk density and inefficient water use.

Drip irrigation.

Drip irrigation is one of the most sophisticated irrigation methods, which supplies water directly into the root zone of the soil, reducing evaporation, deep percolation, and nutrient losses. It is associated with improved water use efficiency and more controlled wetting patterns. Studies have shown that drip irrigation can improve soil moisture retention, reduce bulk density, and limit salinity buildup when water quality is suitable (Abdullateef et al., 2022, Ahmed et al., 2021, Yang et al., 2023). However, where irrigation water contains high dissolved salts, even drip systems may contribute to salt accumulation in a localized zone (Samui et al., 2020).

Surface irrigation

Surface irrigation is widely practiced in small-scale systems and involves gravity-driven water flow across the soil surface, such as contouring, flooding, and furrowing. Although simple and low-cost, surface irrigation may result in uneven water distribution, increased runoff, deep percolation, and redistribution of salts within the profile. High water volumes may promote nutrient leaching and influence soil pH and salinity dynamics. This supported by Van Koppen et al. (2017) and Samui et al. (2020) furrow irrigation is ineffective because water flows across the land to reach the crops. Thus, this leads to significant water loss from the system through runoff. Some FLI practitioners use this method because most of their farms are relatively small. However, it results in decreased soil quality due to nutrient leaching.

2.7.2. Effects of water quality on soil chemical and physical properties

Irrigation water has direct, measurable effects on soil physical and chemical properties because it serves as both a moisture source and a carrier of dissolved ions. Studies show that repeated application of saline water increases soil electrical conductivity and alters nutrient balance within the root zone (Rengasamy, 2010, Qadir et al., 2014, Sheferia¹ and Seid, 2021). As such, elevated salinity may reduce nutrient uptake efficiency and interfere with nitrogen, phosphorus, and potassium dynamics. Similarly, a high sodium adsorption ratio leads to sodium accumulation on exchange sites, displacing calcium and magnesium and increasing the exchangeable sodium

percentage. This process destabilizes soil aggregates, reduces porosity, and decreases infiltration (Qadir et al., 2014, Sheferia¹ and Seid, 2021). Consequently, soil bulk density may increase, which might ultimately affect soil structure and texture, therefore affecting soil water retention characteristics (Mzezewa, 2025, Gajić et al., 2023). Furthermore, nutrient-rich irrigation water may temporarily increase soil nitrate and phosphorus levels. However, prolonged application may result in nutrient imbalance or leaching losses. Saffan et al. (2024a) compared the effectiveness of different water qualities, observing that the lowest-quality water had the highest soil salinity and exchangeable cation levels compared to water of good quality and partially low quality. Therefore, water quality influences both chemical properties and physical properties, such as pH, EC, available phosphorus, exchangeable bases, SAR, bulk density, porosity, and soil water retention curve (SWRC). These parameters are essential indicators of soil sustainability under irrigation.

2.7.3. The effect of cropping systems on Soil quality.

Farmer-led irrigation practitioners practice different cropping techniques, which influence nutrient cycling, organic matter dynamics, and soil structure within these cropping systems. An intensive intercropping system offers multiple cropping cycles per year, increasing nutrient removal from the soil. Therefore, without adequate nutrient replenishment, soil fertility may decline. A review by Viaud et al. (2018) found that crop rotation in permanent grasslands with temporary grasslands had a significant impact on soil quality compared to cereals and forages. Intercropping systems and diversified cropping patterns may improve soil cover, reduce erosion, and enhance root distribution, thereby influencing soil porosity and aggregate stability. Similar practices are adopted by FLID irrigators. Continuous monocropping, particularly under intensive irrigation, may accelerate nutrient depletion and alter soil chemical balance. However, crop residues contribute organic matter that enhances soil structure, increases cation exchange capacity, and improves water retention. This is supported by Moharana et al. (2017), who observed that pearl millet and a cropping system have significantly altered soil organic carbon pools. Similarly, Srivastava et al. (2016) observed that the sorghum-bweseem fodder system resulted in the best soil quality compared to other vegetable cropping systems. Therefore, cropping intensity and system design directly influence soil organic carbon, nitrate nitrogen, available phosphorus, exchangeable potassium, and soil physical properties such as bulk density and porosity.

2.7.4. The effect of tillage practices on soil quality.

Tillage is an agricultural practice that mechanically mixes soil using tools and can be classed into conservation (no-till and minimum tillage) and conventional (e.g., harrowing and ploughing). Tillage practices modify soil structure, aeration, and moisture dynamics, thereby altering the physical, chemical, and biological properties of soil ecosystems. Different farmers, including FLI farmers, adopt different tillage practices depending on their farm size, labour, and finances, among other factors. Conventional tillage disturbs soil aggregates, increases short-term porosity, and enhances nutrient mineralization. However, repeated disturbances may reduce aggregate stability, increase erosion risk, and promote the loss of organic matter. This is supported by (Cooper et al., 2020) compared conservation tillage with conventional tillage in a UK farm trial. They observed that conservation tillage practices did not alter the soil's physical, chemical, or biological conditions compared with conventional tillage, which can cause soil degradation.

Conservation tillage and reduced disturbance practices enhance soil structure, improve infiltration, and reduce evaporation losses. These practices may decrease bulk density over time and improve soil water retention capacity. Several studies align with the conservation tillage improve total organic carbon, available phosphorus, total potassium, the C:N ratio, and yield, which in turn improved soil structure and biological activity compared to conventional tillage (Juhos et al., 2024, Sadiq et al., 2021, Acir et al., 2022, Nandan et al., 2019). Tillage also affects the distribution of nutrients within the soil profile and influences nitrate mobility and phosphorus availability.

Under irrigation, tillage practices interact with water application patterns to determine infiltration behaviour, salinity distribution, and overall soil structural stability. As such, an environmentally friendly practice is required to conserve water and soil resources, reduce farm energy use, and increase crop yields for farmers, including FLID irrigators.

2.7.5. The effect of inorganic and organic fertilizers on Soil quality.

Fertilizer management can influence soil chemical properties and interact with irrigation water quality and tillage practice. Inorganic fertilizers supply readily available nutrients such as nitrogen, phosphorus, and potassium, enhancing crop growth and yield. However, excessive application may increase soil salinity and contribute to nutrient leaching under irrigation, leading to soil deterioration and ultimately reduced soil fertility and quality. Zhang et al. (2022) observed that inorganic fertilizer improved soil nutrient levels (N, P, K) but reduced the soil organic carbon

fraction compared to inorganic fertilizer + organic manure treatments, and vice versa. Mahmood et al. (2017) observed that soil nutrients (N, P, K, OC) were improved when inorganic fertilizer was applied compared to organic fertilisers, while the application of organic manures buffered soil pH and reduced soil bulk density. This suggests that Organic fertilizers, such as poultry manure, can improve soil organic carbon, aggregate stability, and cation exchange capacity. They can enhance soil structure, reduce bulk density, and improve water retention.

Studies by Hammad et al. (2020) and Sahu et al. (2024) observed that the use of organic manures increased nitrogen, phosphorus, and organic carbon concentrations, thereby positively influencing soil fertility, compared to inorganic fertilizers. The combined application of organic and inorganic fertilizers may improve nutrient use efficiency and sustain soil fertility under intensive irrigation. However, nutrient accumulation from repeated fertilizer application, particularly under saline irrigation, may alter soil electrical conductivity and nutrient balance. Therefore, fertilizer type and rate can influence soil pH, nitrate nitrogen, available phosphorus, exchangeable bases, and soil physical characteristics. Integrated soil fertility management, combining organic and inorganic inputs with appropriate irrigation practices, is essential to maintain soil physicochemical stability and sustain productivity under Farmer Led Irrigation Development systems.

2.8. Determinants of FLID Performance in South Africa

Farm performance is influenced by interconnected environmental, technical, socio-economic, and institutional factors that determine productivity, income generation, and sustainability (Bojnec and Latruffe, 2013). Farmer-led Irrigation Development performance, like any other farming system, is also influenced by many factors. Due to their limited resources, reliable access to irrigation water is a primary determinant, but water quality is equally important to them. Therefore, their knowledge of soil and water management practices is also important because it is crucial for parameters such as EC and SAR in water, which, over time, influence soil salinity, sodicity risk, nutrient availability, and infiltration, thereby affecting long-term soil productivity and, ultimately, farm performance. Additionally, irrigation technologies such as drip and furrow irrigation, farm management practices (including cropping intensity, fertilizer integration, and tillage), and soil physicochemical properties that regulate how irrigation water interacts with the soil (such as texture) all affect soil fertility, farm productivity, and ultimately farm performance. This context still remains undocumented in semi-arid regions of South Africa, including Limpopo province. Bojnec

and Latruffe (2013) measured farm performance through technical efficiency and found out that relatively small farms are less technically efficient but more profitable. Socio-economic factors such as access to capital, technical knowledge, and market linkages further determine the capacity to invest in and manage irrigation systems effectively. Overall, Farmer Led Irrigation Development performance depends on the alignment between water availability and quality, irrigation method, soil condition, management intensity, knowledge of soil and water management practices, and institutional support to ensure both productivity and long-term environmental sustainability.

2.9. Policies, institutions, and water governance arrangements

Policies, institutions, and water governance arrangements vary and shape the environment within which farmer-led irrigation development (FLID) operates globally and in South Africa. Globally, there is increasing recognition that supporting FLID can be more cost-effective than investing exclusively in large-scale irrigation schemes. As an alternative to making significant expenditures in irrigation schemes, the World Bank currently recommends that governments direct irrigation policies and development support to FLID (Duker et al., 2023a). In South Africa, this shift aligns with broader efforts to strengthen smallholder participation and improve rural livelihoods.

South Africa has a comprehensive policy and institutional framework to sustain water resources and enhance agricultural productivity. Key legislation includes the National Water Act of 1998, which establishes water as a national resource held in trust by the state and promotes equitable, efficient, and sustainable use (Dirwai, 2019, Machethe, 2004). The Water Allocation Reform Policy further seeks to address historical inequities in water access, particularly in the agricultural sector. At the provincial level, water governance arrangements operate within designated Water Management Areas, where irrigation water use varies significantly. For example, irrigation accounts for approximately 75% of water use in the Limpopo, Luvuvhu, and Letaba Water Management Areas, compared to lower proportions in other regions. These variations reflect differences in agricultural intensity and hydrological conditions, and the biggest issue facing South Africa is a lack of local competence to manage water. Studies have revealed that the absence of competent water managers in several municipalities has led to these municipalities' incapacity to adhere to water management quality criteria (Schreiner and Hassan, 2010).

Institutional Arrangements

Farmers' profitability in irrigation schemes can be affected by institutional arrangements (Kadyampakeni et al., 2014). Institutions responsible for implementing water policy include the Department of Water and Sanitation, Catchment Management Agencies, Water User Associations, and the Water Research Commission. Catchment Management Agencies oversee basin-level planning and stakeholder participation, while Water User Associations coordinate local water distribution and management among irrigators. The Water Research Commission supports research and knowledge generation to inform water management practices. Despite strong policy frameworks, governance challenges persist. A major constraint in South Africa is the limited local institutional capacity to manage water effectively. The irrigators' own autonomy wasn't taken into account when they were designed because institutions have not changed to meet the sector's changing challenges and possibilities, among other reasons (Dirwai, 2019, Phakathi et al., 2021, Van Averbeké et al., 2011b). These studies have shown that some municipalities lack the technical competence required to meet water management quality standards. Weak institutional arrangements have historically contributed to the poor performance of smallholder irrigation schemes. In many cases, irrigation systems were designed without sufficient consideration of farmer autonomy, participation, and local context. Institutional structures imposed externally often lacked legitimacy and farmer ownership, thereby reducing effectiveness. Evidence suggests that institutions perform better when they are socially and politically accepted and when farmers are treated as active agents rather than passive beneficiaries.

Policy arrangements

Institutions, protocols, and processes must be followed when creating a policy for it to be deemed socially acceptable. Since cultures and nutritional demands vary, irrigation schemes cannot have a single policy, strategy, or set of procedures that applies to all of them. As a result, irrigation schemes are not created equal. Traditional farming techniques in South Africa were disrupted by the segregationist regulations that prevailed until 1994. Due to these stringent policies, native African landownership accounted for only around 13% of all arable land in 1994 (Nieuwoudt & Groenewald, 2003). Policymakers have steadily acknowledged the role that small-scale irrigation farming plays in enhancing improved rural livelihoods. Growth, Employment, and Redistribution (GEAR) replaced the RDP as South Africa's overarching development policy following a policy reform. By supporting community-based initiatives rather than privatizing development, the strategy redefined the goal of eradicating poverty. The designated drivers of the rural areas' progressive economic absorptive ability were already existing irrigation facilities. However,

rejuvenation was necessary before the schemes realized increased efficiency. Thus, in accordance with Denison and Manona (2007), the Revitalization of Small-holder Irrigation Schemes (RESIS) was started.

Water governance arrangements

Water governance refers to the political, social, economic, and administrative systems through which water resources are developed and managed. Effective governance requires continuous adaptation to changing climatic conditions, water demand, and agricultural intensification. In the context of Farmer Led Irrigation Development, governance arrangements must balance regulatory oversight with farmer autonomy. This includes ensuring compliance with water-use licensing, protecting groundwater resources, promoting water-quality monitoring, and strengthening institutional coordination between the water and agricultural sectors.

2.10. Discussion and Conclusion

Currently, irrigated agriculture is promoted as the ideal substitute for rain-fed agriculture to ensure food security, particularly in regions with lower rainfall (Chidavaenzi et al., 2021). Moreover, small-scale irrigation gained popularity. However, due to a combination of economic and infrastructural factors and massive investments, most of the SIS in South Africa, along with their water users, have reported below expectations and continued to fail (Phali et al., 2022). In addition, the transfer of land to small-scale farmers and the revitalisation of irrigation schemes failed. Independent irrigation through FLID initiatives drives the expansion of irrigated agriculture (Cousins, 2013). Hence, FLID has received increased attention recently in the literature on SSA (Burney et al., 2013, De Fraiture and Giordano, 2014). However, there has been little qualitative and quantitative analysis of FLID and its interactions in many parts of the world, including South Africa.

The nature of FLID is diverse and has been described in different ways, with a wide range of water sources, conveyance mechanisms, land sizes, irrigation systems, crop varieties, and levels of investment. In this study, FLID is defined as a process where farmers alone or as a group play a driving role in improving their water use for agriculture by taking the lead in the establishment, improvements, and bringing about changes in knowledge production, technology use, investment patterns, market linkages, and the governance of land and water (De Fraiture and Giordano, 2014, Harmon et al., 2023, Nkoka et al., 2014, Veldwisch et al., 2019, Wiggins and Lankford,

2019, Woodhouse et al., 2017). Studies showed variation in soil and water management practices depending on land use, financial capabilities, and area, resulting in different practices at different scales of operation among small-scale farmers.

Furthermore, research revealed that irrigated area established by farmers is not included in the government's statistics, and FLID, which is primarily informal, falls into the group of farmers who are rarely recorded (Woodhouse et al., 2017, Venot et al., 2021, Beekman et al., 2014). This is because these informal irrigation setups are small-scale, fragmented, hard to count, and sometimes hard to detect; hence, they are mostly underreported (Venot et al., 2021). Therefore, there is a need to generate knowledge, characterize, and document the status of FLID in South Africa, along with the associated soil and water management practices.

2.10. References

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CHAPTER THREE: CHARACTERIZATION AND PERFORMANCE DETERMINANTS OF FARMER-LED IRRIGATION DEVELOPMENT (FLID) IN VHEMBE DISTRICT, SOUTH AFRICA

Abstract

Farmer-led irrigation development (FLID) is gaining prominence in Africa for accelerating irrigation expansion and agricultural productivity. However, little is known about FLID, its characteristics, and the determinants of its performance in South Africa. The aim of this chapter is to characterise the FLID in South Africa using the Vhembe District as a case study and further assess the factors influencing the performance of FLID. The study used purposive and snowball sampling techniques to identify 66 FLID farmers in the subtropical regions of Thulamela and Makhado Municipalities in Vhembe District. The data was collected a structured, in-depth interviews. Descriptive statistics were used to characterize farmers and farming systems, including land size, irrigation technologies, cropping systems, soil and water management practices, institutional support, and perceptions of climate change. Principal component analysis (PCA) was applied to derive composite indices of soil management, irrigation practices, and water-saving knowledge, and a Multiple Linear Regression (MLR) model was used to assess their influence on farm income. Findings from the study revealed that most FLI farmers were older than 60 years, well educated, and relied mainly on a pension to supplement the purchase of farming inputs and household consumption. Furthermore, FLI farmers rely on boreholes as their primary water source. The land sizes predominantly range from 1 to 5 hectares, and the farmers plant a diverse mix of high-value crops (vegetables) and staple crops under a drip irrigation system. However, the results revealed that they face several challenges, including limited institutional support (financial and extension support), inadequate storage infrastructure, and being highly vulnerable to climate change. PCA identified six management and land condition dimensions, of which integrated soil and water-saving knowledge (PC1) and irrigation capacity and scheduling (PC2) significantly increased farm income. A fishbone analysis highlighted high investment and operating costs, as well as weak institutional linkages, as major drivers of FLID underperformance. The findings underscore the need for tailored policies and interventions that target improved irrigation technologies and soil–water management with accessible finance, responsive extension, and recognition of FLID within water governance frameworks in South Africa.

Keywords: Farmer-led irrigation development, soil and water management, Irrigation practices, farm performance.

3.1. Introduction

Agriculture consumes approximately 60% of water resources in South Africa, with a significant portion going towards irrigation (Bonetti et al., 2022). According to Cai et al. (2017) there is significant expansion in irrigated agriculture, mainly driven by Farmer-Led Irrigation Development (FLID), than what is officially documented. Farmer-led irrigation development involves a diverse group of independent farmers or groups of farmers taking the lead in acquiring and setting up irrigation infrastructure in their farms, outside formal irrigation schemes (Woodhouse et al., 2017, Wiggins and Lankford, 2019). FLID is characterized by small-scale operations, limited resources, and market-oriented production of horticultural crops, which depend on family and community labor (African Union, 2020). FLID offers adaptable solutions that extend beyond state-owned irrigation schemes, improving agricultural productivity and enhancing irrigation development and water management in the agricultural sector.

FLID has been extensively studied across Africa, and national policies have recognised and supported FLID in countries such as Ghana, Mozambique, Tanzania, and Ethiopia (Woodhouse et al., 2017, Dittoh, 2020, Kafle et al., 2020). For instance, FLID in Ethiopia was projected to expand from 2.3 million hectares to 4.1 million hectares in Ethiopia in 2020, facilitated by the national development plans such as the Growth and Transformation Plan II, 2016-2020 (Woodhouse et al., 2017, Dittoh, 2020, Kafle et al., 2020). In contrast, there is no comprehensive empirical documentation and development of FLID in South Africa. Existing research in South Africa has largely focused on state-led irrigation schemes, leaving a gap for investigations into FLID systems, their characteristics, and performance. FLID farmers employ various agricultural water management (AWM) practices and soil management practices that may differ significantly due to factors such as farm size, farmers' knowledge and education levels, and access to resources.

Agricultural Water Management (AWM) practices and technologies, including water abstraction, conveyance systems, and irrigation application methods, play a central role in shaping the efficiency and sustainability of FLID systems (Woodhouse et al., 2017). Additionally, these AWM practices are complemented by soil management practices, including tillage and cropping

systems. Together, these agricultural soil and water management practices can be defined as actions that enhance water availability in the root zone and improve water-use efficiency, soil health, input utilization, and overall farm productivity (Van Koppen et al., 2017, Denison, 2020). This approach can evaluate the integration of soil and water management practices that influence irrigation efficiency, soil health, and overall farm productivity, thereby determining the performance and long-term viability of FLID systems. Proper AWM, coupled with farming practices, can mitigate the adverse effects of climate change on agriculture by doubling or tripling farming intensity and increasing global food security (Denison, 2020, Van Rooyen et al., 2017).

The Vhembe District in Limpopo Province presents one of the most compelling environments for studying FLID in South Africa because of its agro-ecological diversity, declining rainfall trends, and increasing drought frequency (Makungo et al., 2019, Pieterse et al., 2024). This variability significantly increases the need for reliable irrigation. Irrigation has been identified as one of the critical strategies to enhance agricultural production, farm income, and household food security in this changing climatic environment for the growing population in Sub-Saharan Africa (SSA) (Zougmore et al., 2018, Materechera and Scholes, 2022). Understanding the AWM and farming practices in Vhembe district is crucial for accurately assessing FLID productivity and sustainability, as well as farmers' adaptation to changing environmental constraints. Furthermore, FLID performance depends on multiple and interacting determinants, including water availability, labour, finance, management practices, markets, and technology (World Bank, 2021). Despite the importance of these factors, evidence of their influence on performance outcomes such as farm income and water-use efficiency remains underexplored. Therefore, this study aimed to address these knowledge gaps by:

1. Identifying and characterizing FLID in South Africa using the Vhembe district as a case study,
2. Assessing the factors that influence the performance of the FLID system.

3.2. Research Methodology

This chapter presents the study site, research design, data collection tools and procedures, and data analysis.

3.2.1. Description of the Study Area

The study was conducted in the Thulamela and Makhado local municipalities in Vhembe District, Limpopo Province, South Africa. The Vhembe District is located at 22.7696° S, 29.9741° E in the far north of the Limpopo Province (Figure 3.1). Thulamela and Makhado municipalities are situated on the southern side of Vhembe District, and they cover a total area of 831,058.64 hectares and 289,393 hectares, respectively (Mbulaheni, 2021). The Thulamela and Makhado municipalities lie in a subtropical regional hub with significant precipitation of more than 700 mm annually, which makes them suitable for cultivating subtropical fruits, cereals, vegetables, and nuts (Materechera and Scholes, 2022, Oni et al., 2011). Agriculture in the Vhembe district is one of the economic drivers of Limpopo Province. According to Rusere et al. (2019) The Vhembe district is primarily rural, with 90% of the population relying on agriculture to sustain their livelihoods and drive economic development. Small-scale agriculture accounts for a substantial share (70%) of farming activities in the Vhembe district, with commercial agriculture accounting for the remaining 30% (Odhiambo and Magandini, 2008, Olofsson, 2020, Oni et al., 2012).

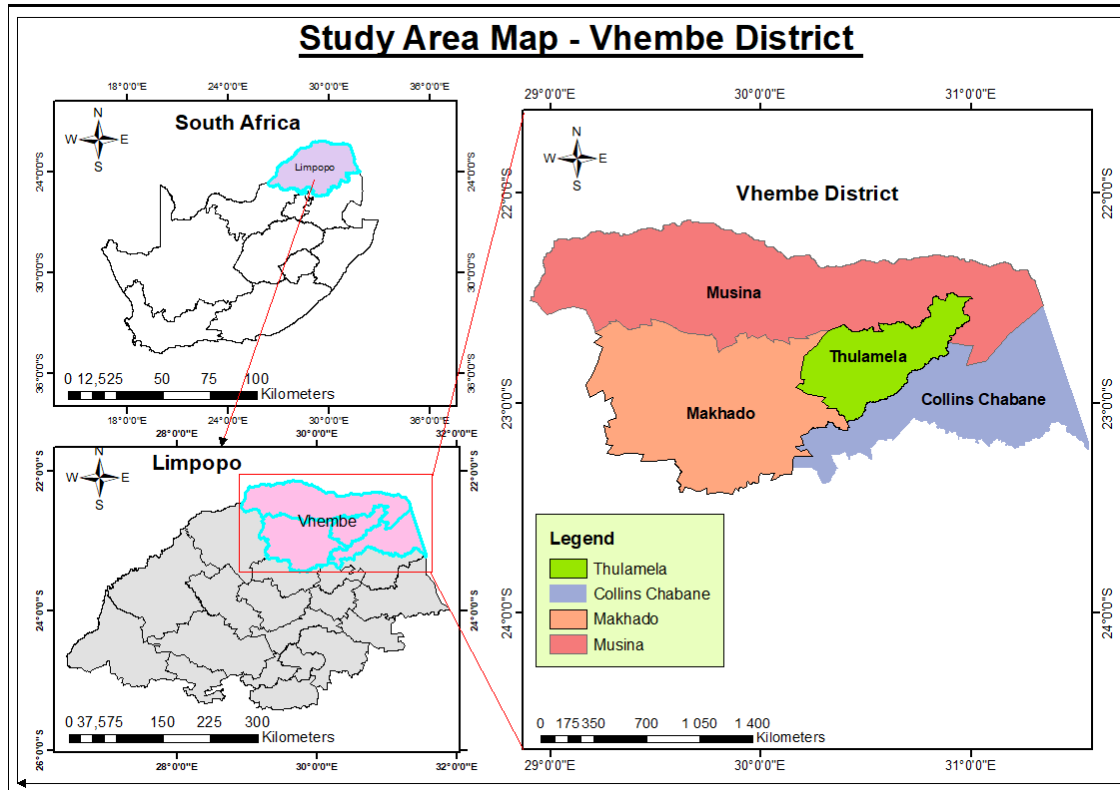


Figure 3.1: Map of study area, Vhembe District, showing four local municipalities (Source: Author's computation)

3.2.2. Sampling procedures

The population of farmers involved in FLID is unknown. Hence, the construction of the sampling frame involved collaboration with the local Departments of Agriculture and Rural Development in the Thulamela and Makhado municipalities. Furthermore, focus group discussions with extension officers from each municipality were conducted to identify and include all eligible farmers who engage in FLID. The study employed both purposive and snowball sampling methods to select 66 farmers from the two local municipalities. The process of sampling FLID farmers began with the initial identification of participants through referrals by extension officers and community members in the municipalities and continued until the municipality was exhausted/no further referrals were made. The use of snowball sampling benefited the study by enabling the recruitment of FLID farmers who were previously difficult to reach due to their anonymity.

3.2.3. Data collection

Primary data were collected through face-to-face interviews using a structured questionnaire comprising both closed- and open-ended questions, allowing FLID farmers to provide detailed, descriptive responses (Appendix C). The questionnaire focused on farm characteristics, irrigation and water management practices, and soil management practices. Furthermore, the field data focused on the factors that influence the performance of FLID, and follow-up questions were issued to capture the diverging viewpoints of the respondents. Prior to data collection, ethical clearance was obtained from the University of Venda's Research Ethics Committee, and gatekeeper letters were obtained from the Limpopo Department of Agriculture and Rural Development (LDARD) to permit data collection. The questionnaires were reviewed by various parties to ensure validity and reliability, and a pilot test was conducted with FLID farmers who did not form part of the 66 farmers used in the study to improve the quality and effectiveness of the primary research.

3.2.4. Data analysis

The Statistical Package for the Social Sciences (SPSS) version 29 software was used to capture and analyse the data. Descriptive statistics were used to analyse and summarize the demographic and socio-economic characteristics, including percentages and frequency counts presented in tabular form, as well as bar graphs and histograms. Moreover, principal component analysis, multiple linear regression, and a fishbone diagram were used to derive insight from the data.

3.2.5. Principal Component Analysis (PCA)

The Principal Component Analysis (PCA) was employed to summarise multiple, potentially correlated indicators and principal components (PCs) of soil and water management and perceived land conditions into a smaller number of composite components for further analysis. Subsequently, multiple linear regression (MLR) was employed to assess the effect of the PCA-derived management and land condition components, as well as irrigation training, on farm performance, with annual farm income serving as the dependent variable. The use of PCA-derived factor scores in the regression model enabled the inclusion of multiple interrelated soil and water management factors without violating the multicollinearity assumptions. Finally, a

fishbone (Ishikawa) diagram was used as a visual synthesis tool to organise and summarise the main factors associated with the performance of FLID in Vhembe District, based primarily on the descriptive analysis results.

3.3. Results and Discussion

3.3.1. The overview of demographic and Socio-economic characteristics of FLI farmers

The results of gender, age, marital status, household head, and household size are presented in Figure 3.2. The results revealed that male farmers were the dominant group, accounting for 75.8%, while female farmers accounted for only 24.2%. The results of male dominance are consistent with relevant studies in the Vhembe district, where the high dominance of men in small-scale farming may result from cultural norms and values in the study area (Materechera and Scholes, 2021b, Jiba et al., 2024, Mdoda et al., 2022, Maponya, 2021). The lower percentage of female farmers may be attributed to women often being assigned household tasks rather than taking over farm production. The small number of female farmers participating in agriculture suggests that they may come from households where they are the household heads. This concurs with the findings by Mulinya (2017) who reported that female dominance among small-scale farmers in Kenya was likely due to female farmers being the household head, male migration, or their ability to balance household chores and fieldwork.

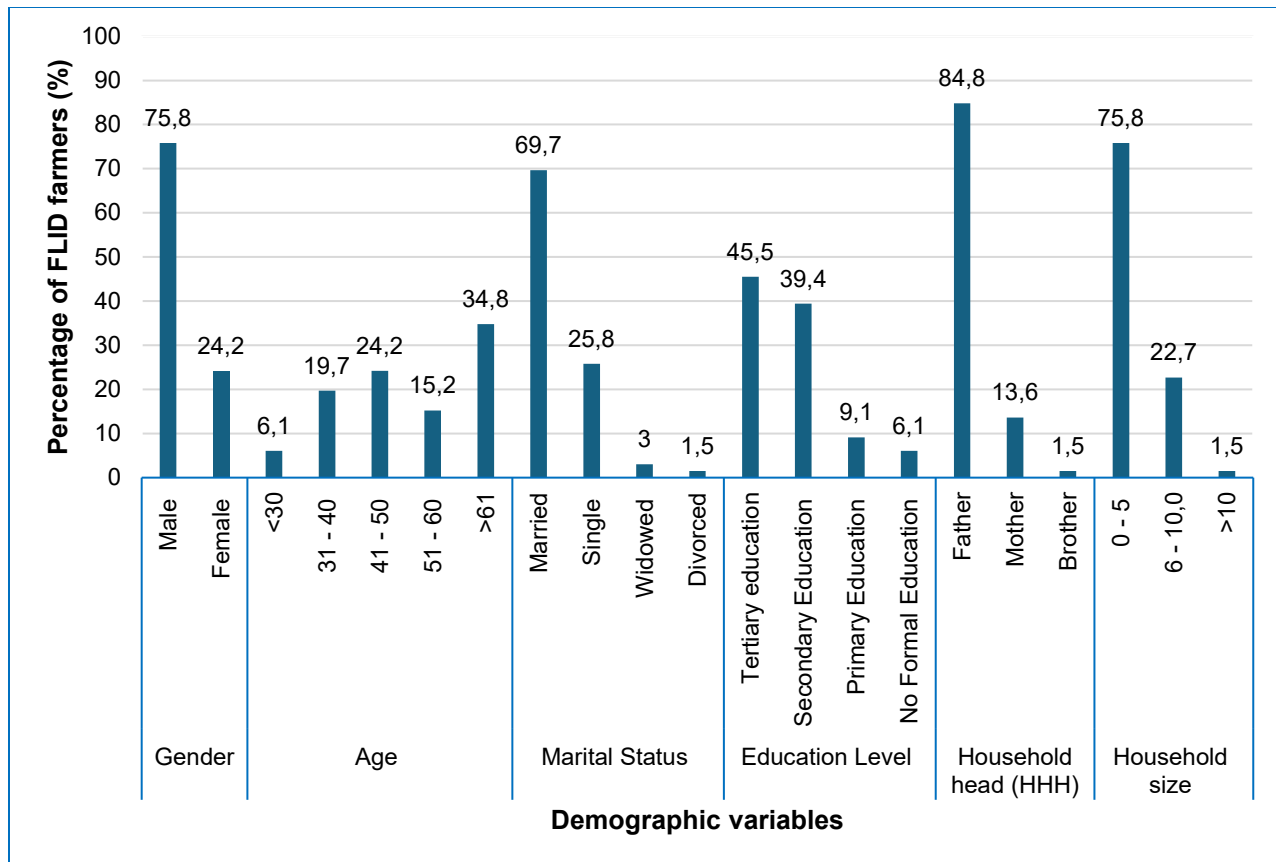


Figure 3.2: Demographic composition of FLID farmers (gender, age groups, marital status, household headship, household size) in Vhembe District

The FLID farming population is dominated by older farmers, with the 60+ age group accounting for 34.8%. This is followed by the age group of 41–50 years with 24.2%, and the least represented group was the age group below 30 years. A similar trend of Vhembe’s aging irrigation population was observed in a study conducted by Materechera and Scholes (2021b) who reported that 90% of the farmers were aged 51 or older. Although this is significantly higher than the 50% obtained in this study, both studies imply substantial farming experience among the majority of farmers and also indicate potential succession challenges in the future. Although the study indicates very little interest in agriculture among the age group below 30 years, there is increasing interest among the youth in the 31–40 years age group, accounting for 19.7% of the FLID farmers. According to Mulinya (2017) the farmers in the age group of 30 – 34 years are likely to grasp and understand challenges in farming systems and are regarded as better equipped with adequate and relevant information. This is consistent with the farmer-driven initiatives that drive FLID and may be the reason for the increase among the 31-40-year age group compared to the under-30 age group. Figure 3.2 further illustrates the educational levels of the farmers, with 6.1% having no formal education, followed by those who attended primary school (9.1%) and secondary school (39.4%).

The majority of farmers in the study area have attained tertiary education (45.5%), indicating that FLID farmers possess the necessary skills and knowledge to implement and invest in modern agricultural practices. This is consistent with findings by (Mulinya, 2017) this showed that tertiary education enhanced farmers' knowledge and skills, enabling them to better adapt to environmental constraints and access information on various media platforms.

In this study, gender, marital status, and household headship are closely interconnected and shape labour allocation, decision-making, and access to irrigation resources in Farmer-Led Irrigation Development systems. The predominance of male-headed households (84.8%) reflects control over land, water, and capital, while female-headed households (13.6%) may face greater resource constraints despite women's strong involvement in daily farm operations. The high proportion of married farmers (69.7%) suggests reliance on family labour, strengthening irrigation management and cropping intensity. Smaller household sizes (0–5 members; 75.8%) indicate moderate labour availability, which influences farm operations and adaptation capacity. These overlapping socio-demographic factors directly affect technology adoption, resource allocation, and overall farm performance.

Socio-economic characteristics of FLI farmers

The socio-economic characteristics of FLID farmers are shown in Figure 3.3. According to the study, 77.3% of FLID farmers reported having an off-farm source of income, suggesting that FLID farmers explore other options for income to avoid relying solely on farming income, thereby demonstrating a diversification strategy. Most of the off-farm income was derived from pensions, government grants, and remittances, accounting for 27.3%, 25.8%, and 24.2%, respectively. This is consistent with the findings of (Olofsson, 2020) and Materechera and Scholes, (2022) who reported that a significant proportion, 41%, of small-scale irrigators in Vhembe district rely heavily on state pensions as their primary livelihood source and government grants due to low farm income (Materechera and Scholes, 2022, Olofsson, 2020). The overreliance on pension funds as a source of off-farm income is consistent with demographic data showing that most farmers are pensioners aged 60 or older. A smaller fraction of FLID farmers receives off-farm income from part-time work (13.6%) and from full-time jobs (9.1%). This may be linked to the smaller demographic of FLID farmers in the age groups below 30 years and 31 – 40 years.

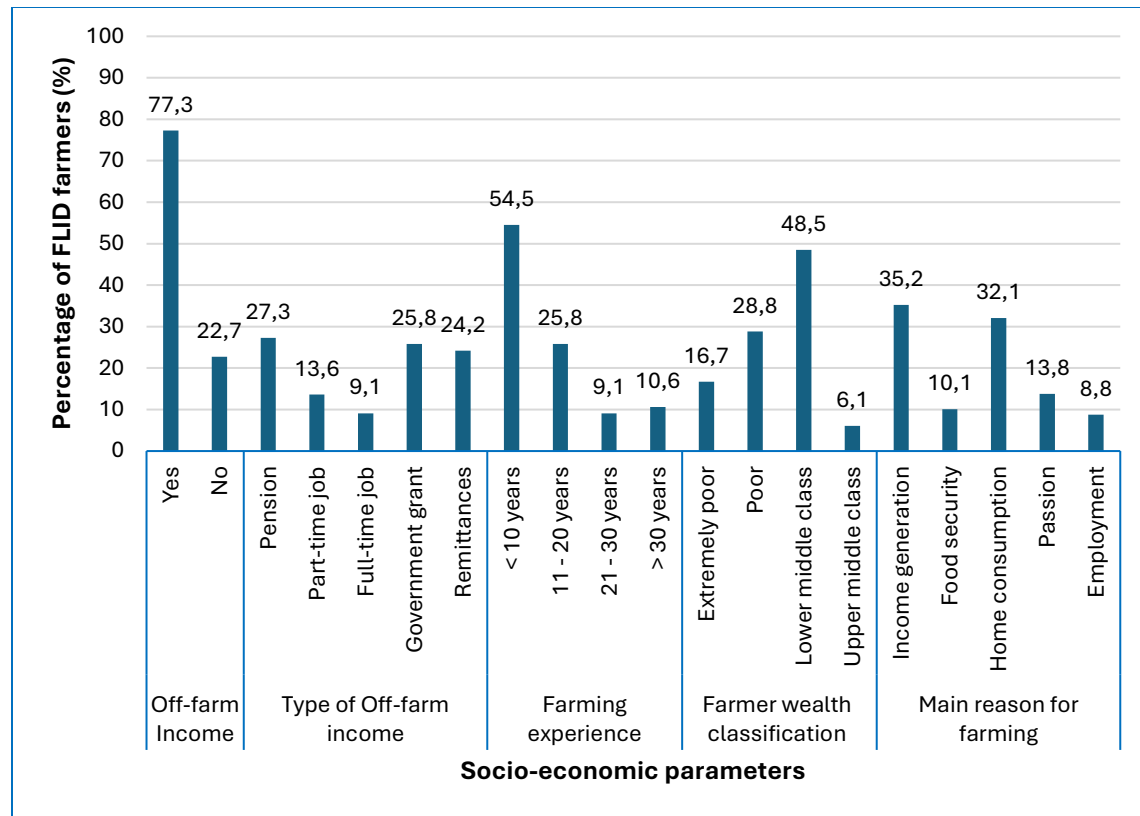


Figure 3.3: Socio-economic profile of FLID farmers (off-farm income source, wealth class, farming experience).

The results show that 54.5% of farmers had less than ten years of farming experience (Figure 3.3), indicating that a considerable number of farmers in the study were relatively new to agriculture. Farmers with 11–20 years of farming experience accounted for 25.8%, whereas those with 21–30 years and 30 years or more of experience constituted 10.6% and 9.1% of the respondents, respectively. The results affirm that FLID is a recent phenomenon, which explains the moderate level of farming experience among the majority of FLID farmers. According to Figure 3.3, the income distribution indicates that Farmer Led Irrigation Development farmers are generally middle class, with 48.5% classified as lower middle class and 6.1% as upper middle class, totaling more than 50%. This socioeconomic positioning suggests a relatively stronger capacity to mobilize financial resources for investment in boreholes, pumps, drip systems, and agricultural inputs. Their economic stability likely enhances their risk-bearing capacity and supports reinvestment in irrigated production. This aligns with the finding that 35.2% practice irrigation primarily for income generation and that 92% perceive farming as a business. Together, these results indicate that FLID in the study area is driven by commercially oriented farmers.

The study also found that most of the FLID farmers practice farming for income generation, accounting 35.2%, followed by home consumption, accounting 32.1%, farmers who do farming for passionate, accounting 13.8%, followed by farmers farm for to cater food security in the community since its rural and the community can go to shops since its far, and they are expensive, accounting 10.1% and lastly others do farming to create employment for the community, accounting 8.8%. These results align with existing literature in Vhembe, where irrigation is driven by the need for income and food security, despite challenges in producing staple crops (Oni et al., 2011).

3.3.2. Land characteristics and soil characteristics

The variation in land characteristics among FLID farmers is presented in Figure 3.4. The land sizes of FLID farmers range from under 1 hectare to well over 30 hectares, with a majority (48.5%) having land sizes between 1–5 hectares (Figure 3.4). Land utilisation is also concentrated within the 1–5 hectare range, accounting for 72.7%, confirming that the optimal land size for FLID farmers is within this range. The results indicate that only 3% of the farmers used between 10.1 and 20 hectares, whereas no farmers used more than 20 hectares. This could be due to insufficient labor, limited resources, and a lack of external support.

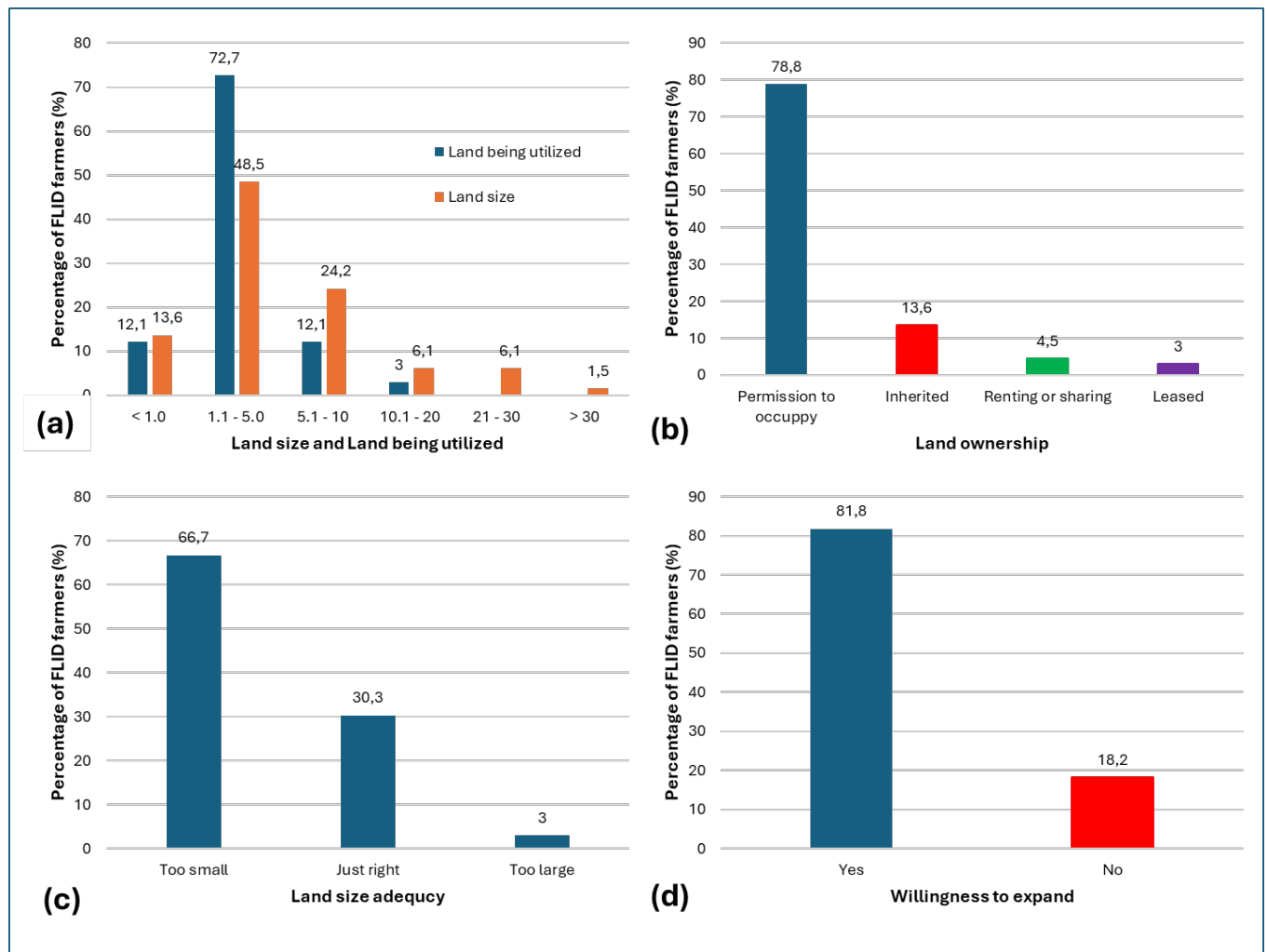


Figure 3.4: The land categories among FLID farmers. **(a)** Land size vs land utilized. **(b)** Land ownership. **(c)** Land size adequacy. **(d)** Willingness to expand

The study revealed that none of the respondents held formal title deeds (Figure 3.4). However, most operated under Permission to Occupy (PTO) certificates (78.8%) issued by traditional authorities, while others accessed inherited customary (ancestral) land. In South Africa's communal areas, PTO and inherited land provide recognized use rights and operational control but do not confer registered ownership (Cousins, 2008; Department of Rural Development and Land Reform, 2013). Because these rights are not legally transferable or mortgageable, they cannot be used as collateral for formal credit, which typically requires title deeds. Consequently, despite having effective control over land, farmers face structural constraints in accessing finance for investment and irrigation expansion.

The study revealed that none of the respondents had title deeds to their lands. A significant majority had Permission to Occupy (PTO) certificates issued by the traditional authorities, at 78.8%, followed by those who inherited the land, at 13.6%. These farmers have complete control over their farms and can implement any effective management practices they choose to improve long-term agricultural productivity. In the study area, renting was short-term and seasonal (about 3–6 months per cropping season), usually based on verbal agreements with limited security, whereas leasing covered longer fixed periods (commonly 1–5 years) and was more likely to involve written agreements, offering relatively greater tenure security. This pattern is consistent with evidence from smallholder and FLID contexts, where seasonal rental markets dominate due to flexibility, while longer-term leases better support investment incentives. However, in communal areas, even leases are seldom formally registered, limiting their enforceability and investment potential. The study reveals that 66.7% of farmers consider their land small, suggesting it is too small for their needs. In contrast, 30.3% perceive the land as the right size, while only 3% find it too big. Despite the fact that the majority of farmers (81.8%) are willing to expand their farms, this suggests that FLI farmers want to grow and improve their livelihoods, while only 18.2% are not willing to expand.

Distribution of Soil types in FLID farms

Figure 3.5 presents the distribution of soil types across Farmer-Led Irrigation (FLID) farms in the Vhembe District. Loamy soils accounted for 47% of the farms, followed by clay soils, and sandy soils at 25.8%, and 15.2%, respectively. Meanwhile, 12.1% of the farmers were unsure of their soil type. This distribution of soil types aligns closely with Vhembe's documented soil information, where the soil types tend to be loam dominant in eastern zones (higher clay/loam content), sandy soils are widespread in the west, and clayey soils throughout (Materechera and Scholes, 2022, Rusere et al., 2019, Moeletsi et al., 2013). Furthermore, Moeletsi et al. (2013) stated that, apart from varying soil types, most of the study's sites had Hutton and Glenrosa types of soil, (SA Soil Classification, 1991). Both soils are characterized to moderate to high sand, moderate silt and low to moderate clay, as classified by the South African soil classification

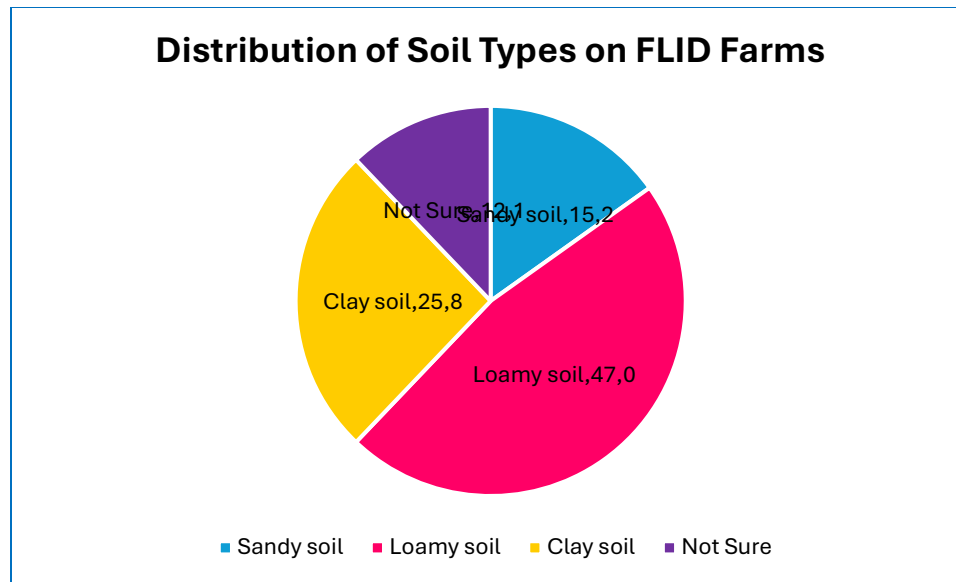


Figure 3.5: The distribution of soil types across Farmer-Led Irrigation (FLID) farms in the Vhembe District

Soil conditions (drainage and fertility perception)

Figure 3.6 illustrates FLID farmers' perception of their soil quality based on their personal assessments. Regarding drainage, 48.5% of the farmers reported fair conditions, indicating moderately drained soils that may occasionally experience waterlogging during peak irrigation. This may imply slow infiltration, which can lead to runoff, particularly with surface irrigation. About 39.4% of the farmers viewed their land as having good drainage, which is ideal for most crops, while only 12.1% reported poor drainage, which may lead to reduced aeration, increased waterlogging, and ultimately hinder crop growth. The farmers' perception of drainage concurs with the findings of (Materechera and Scholes, 2022, Rusere et al., 2019) on the soil drainage conditions in several irrigation schemes in Vhembe, due to possibly similar soil types, as most of the soil types were clay loam soils. A similar distribution pattern is observed in water-holding capacity (WHC), with 51.5% rating their soils as fair, 37.9% as good, and 10.6% as poor, consistent with clay loam soils.

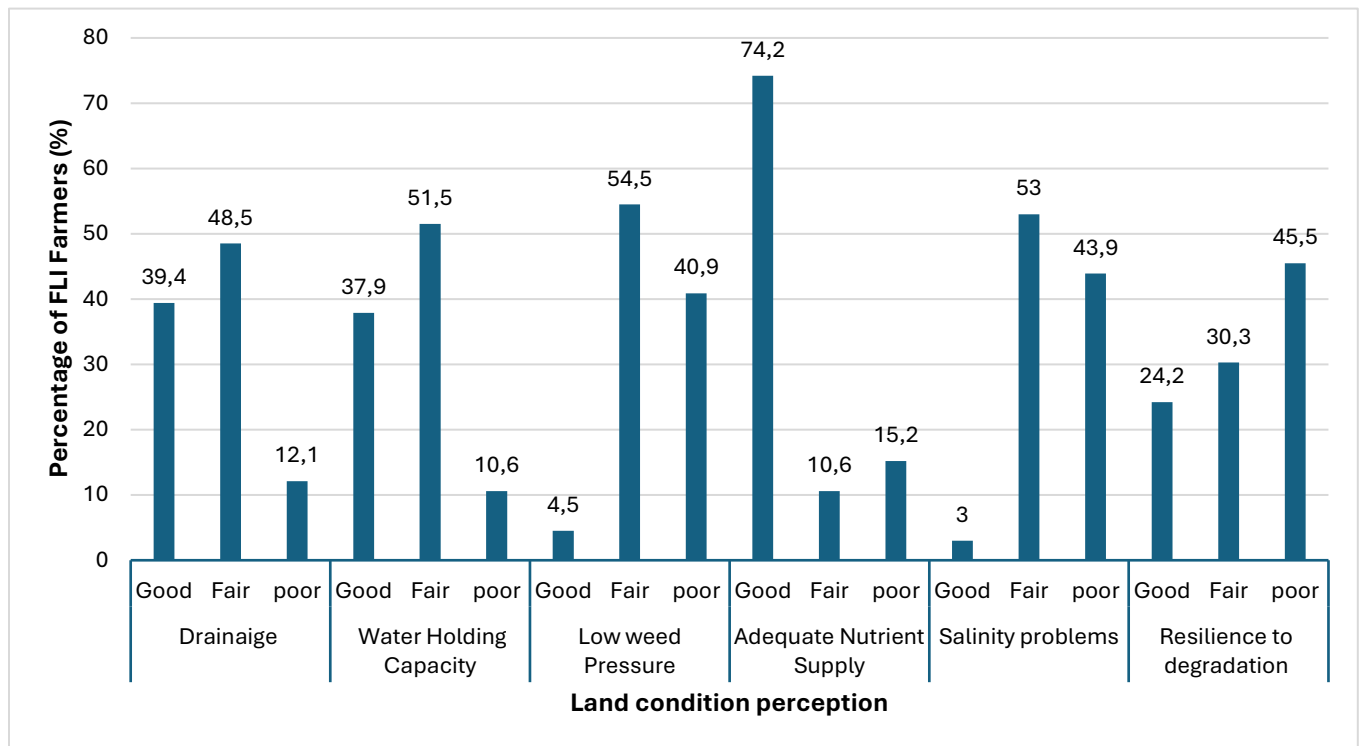


Figure 3.6: Farmer-led irrigation (FLI) farmers' perceptions of land condition

A majority of farmers reported fair weed pressure (54.5%), indicating controllable levels of weeds, whereas 40.9% reported high weed infestation, and only 4.5% reported no weed problems. This result suggests that weeds are a challenge in FLID farms, potentially leading to intense competition for water and nutrients with crops, resulting in reduced water-use efficiency and, consequently, significantly reduced crop growth and yield. Regarding nutrient supply, most FLI farmers rated it as good (74.2%), indicating that nutrient levels are sufficient and optimal for crop growth. 15.2% of the farmers rated their land as poor suggesting the need for fertilizer application to support optimal crop growth.

The findings from this study indicate that soil salinity issues pose a serious challenge in Farmer-led irrigation systems, with 43.9% reporting severe salinity problems, 53% with moderate salinity problems, and only 3% reported no salinity issues. These high salinity levels can often result from shallow groundwater tables, river water, or continuous use of borehole water. This is supported by several studies showing that although most farmers use groundwater, its long-term overuse can cause sodicity or salinity, as it increases Na accumulation and ultimately degrades the soil's physical structure (Rengasamy, 2010, Mohanavelu et al., 2021).

Lastly, resilience to soil degradation is also a significant concern: only 24.2% of farmers rated their soils as good, 30.3% as fair, and 45.5% as poor. This implies that nearly half of the FLID farms are at risk of soil degradation from erosion, crusting, compaction, or loss of organic matter. Low soil resilience reduces crop response to irrigation, increases fertilizer losses, and requires more inputs to maintain productivity. This vulnerability in soils is often associated with improper soil and water management practices on farms, such as over-tilling using conventional methods, inadequate soil cover, and cultivation on slopes without implementing conservation measures. Similarly, (Van Huyssteen and du Preez, 2023) indicated that most South African soils are poor in nutrients, shallow, and acidic, making them susceptible to degradation under more use.

3.3.3. Farming practices (Tillage and cropping systems and soil management practices)

The results of various FLID practices, including tillage, cropping systems, and soil management practices, are presented in Figure 3.7. The results showed that conventional tillage is the most common farming practice, accounting for 72.7%, whereas minimum tillage accounted for 12.1%. Both conservation tillage and mixed tillage practices accounted for 7.6% each. This suggests limited adoption of sustainable tillage practices, which could ultimately affect soil health and long-term productivity. This is evident in several studies where Cooper et al. (2020) compared conventional tillage and conservation and found that with time, conventional tillage may lead to soil degradation, impacting soil physical, chemical, and biological conditions.

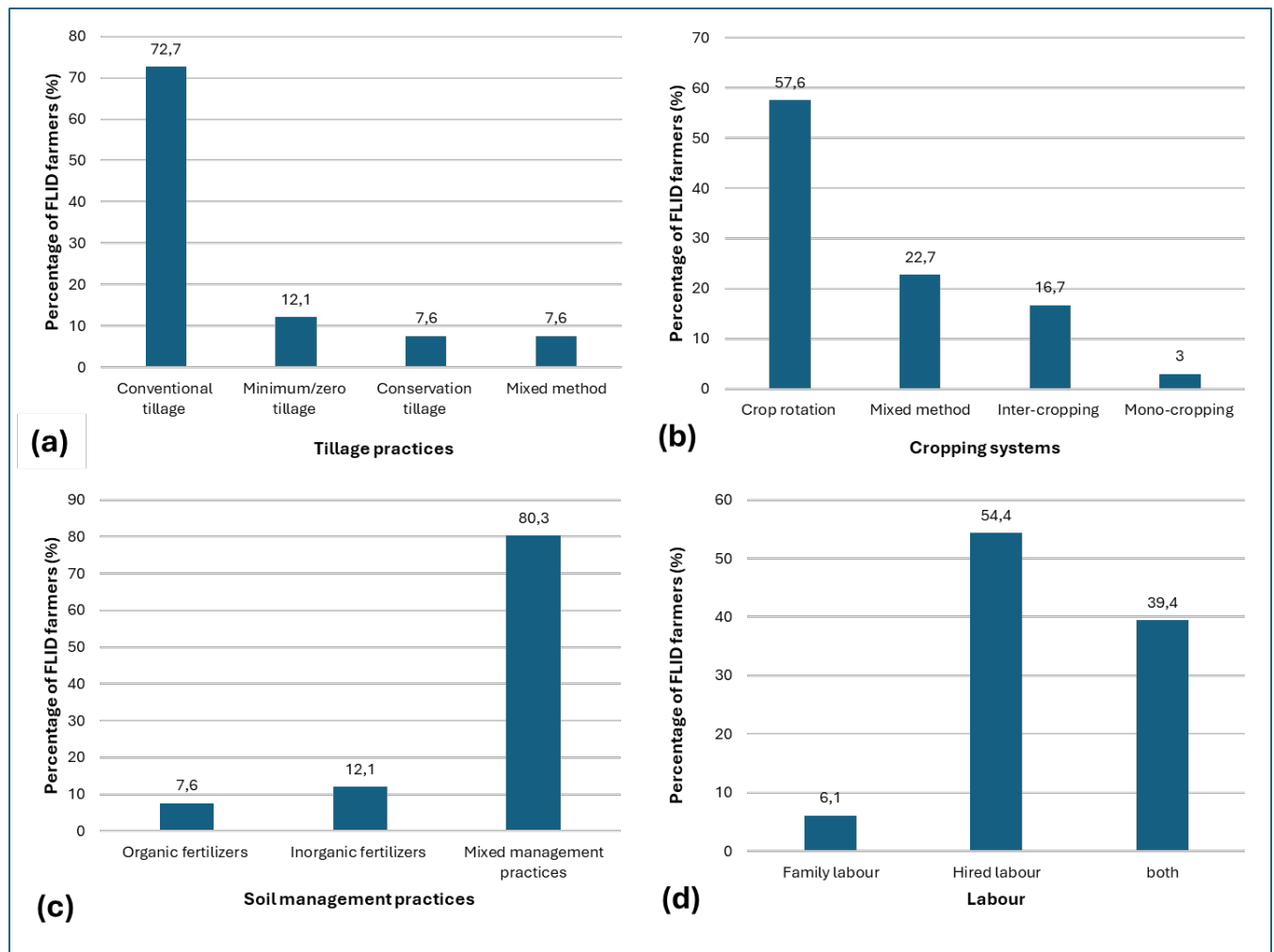


Figure 3.7: Distribution of farming practices among FLID farmers. **(a)** Tillage practices. **(b)** Cropping systems. **(c)** Soil management practices. **(d)** Labour

A majority of farmers practiced crop rotation (57.6%), indicating a high level of knowledge among FLI farmers about its benefits, including improved soil fertility and reduced pest infestations. The results showed that the combination of cropping systems accounted for 22.7%, followed by inter-cropping at 16.7%, and the least preferred cropping system was mono-cropping, accounting for 3%. These results are similar to studies done in the Vhembe district, which reported that maize, legumes, and vegetables are mostly grown in rotation among smallholders, thus improving nutrient cycling (Materechera and Scholes, 2022). Pertaining to soil management practices, many farmers preferred a combination of soil management practices such as cover crops, organic fertilizer, and inorganic fertilizer, accounting for 80.3%, which indicates that FLI farmers want to balance the soil nutrients, followed by 12.1% only applying inorganic fertilizers, which can cause

soil deterioration over time. Lastly, 7.6% only apply organic fertilizers. The low percentages in inorganic and organic fertilizers result from a lack of funding and inadequate extension support. Similarly, Ncube (2020) reported findings among farmers in irrigation schemes who used various manures, compost, and fertilizers to enhance their soils.

3.3.4. Crop production characteristics by the FLI farmers

According to the study's results, as depicted in Figure 3.8, the surveyed group of FLID farmers grow a wide range of vegetables, legumes, and cereals. The most commonly grown crops are green leafy vegetables, such as spinach and mustard, accounting for 15% and 14.9%, respectively. These are followed closely by staples such as tomatoes, butternuts, and maize, which account for 9.7%, 8.6%, and 8.2% of the total, respectively. Additionally, these are followed by okra, which accounts for 7.5%. The most widely grown leafy green crops and staples reflect both dietary preferences and market demand, indicating a balance between market orientation and subsistence needs. Similar results were reported by Odhiambo and Magandini (2008) and Obadire (2010) where maize, vegetables, and leguminous crops are primarily grown by small-scale farmers in Vhembe District, and are commonly used for both income and subsistence. According to Soumaila (2021) Vegetables, maize, and beans are mostly produced under irrigation.

FLID farmers prioritize high-demand vegetables and staples while diversifying with smaller-scale specialty crops to meet market demand, enhance food security, income, and resilience. The diversity of crops planted by FLID farmers reflects their adaptability to market trends, climate conditions, and household nutritional needs. Additionally, this has a positive impact on soil health through crop rotation and improved irrigation efficiency. Diverse crop rotations mitigate risks from market or environmental shocks, thereby supporting the economic viability of smallholder irrigation farming. A study by Moharana et al. (2017) of pearl millet found out that pearl millet combined with cropping systems improves soil carbon, and Viaud et al. (2018) revealed that crop rotation had a significant impact on the quality of soil in permanent grassland combined with temporary grassland.

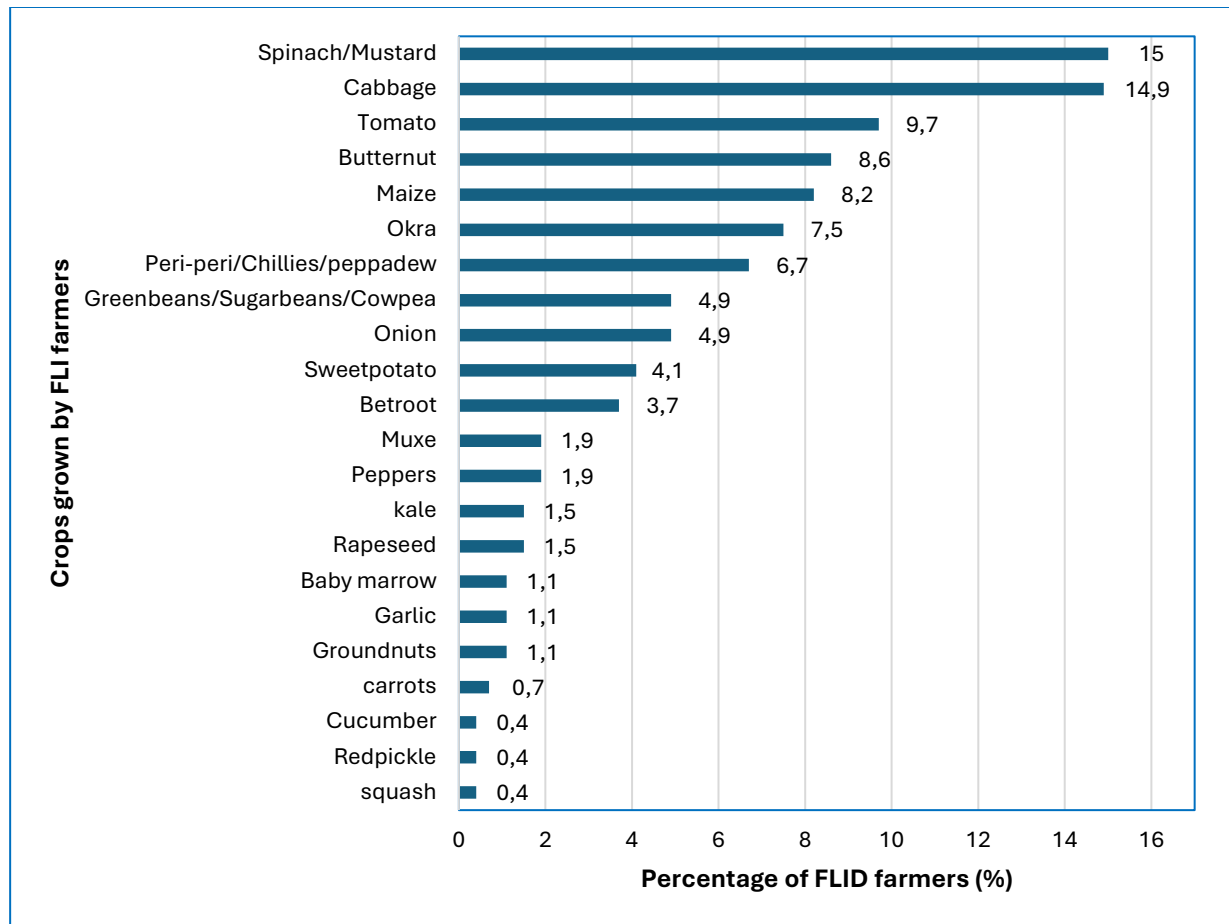


Figure 3.8: Percentage of FLID Farmers cultivating different crops in Vhembe District

3.3.5. Farm Assets, Infrastructure, and Mechanization

Figure 3.9 illustrates the resources among FLID farmers, including various types of agricultural infrastructure and equipment. Regarding water pumps and motorised irrigation systems, 77.3% and 83.3%, respectively, of the respondents reported having these systems (including water pumps, drip irrigation, and sprinklers, among others). 22.7% and 16.7% have no access to water pumps or irrigation systems, respectively, indicating their reliance on gravity-fed irrigation. The high access motorised to irrigation confirms that FLID farmers invest heavily in pumps or drips, or sprinklers, beyond what is typically available to smallholder irrigation schemes (SIS) in South Africa, where their irrigation infrastructure decay limited investment from farmers (Van Koppen et al., 2017, Fanadzo and Ncube, 2018). In contrast, only 28.8% have access to water tanks, and 7.6% have access to reservoirs, highlighting limitations in water storage capacity that may, in turn,

affect irrigation scheduling during dry seasons or periods of water shortage. This limitation matches constraints in SIS during difficult climatic conditions, such as drought and drying of water sources (Dube, 2023, Materechera and Scholes, 2021a).

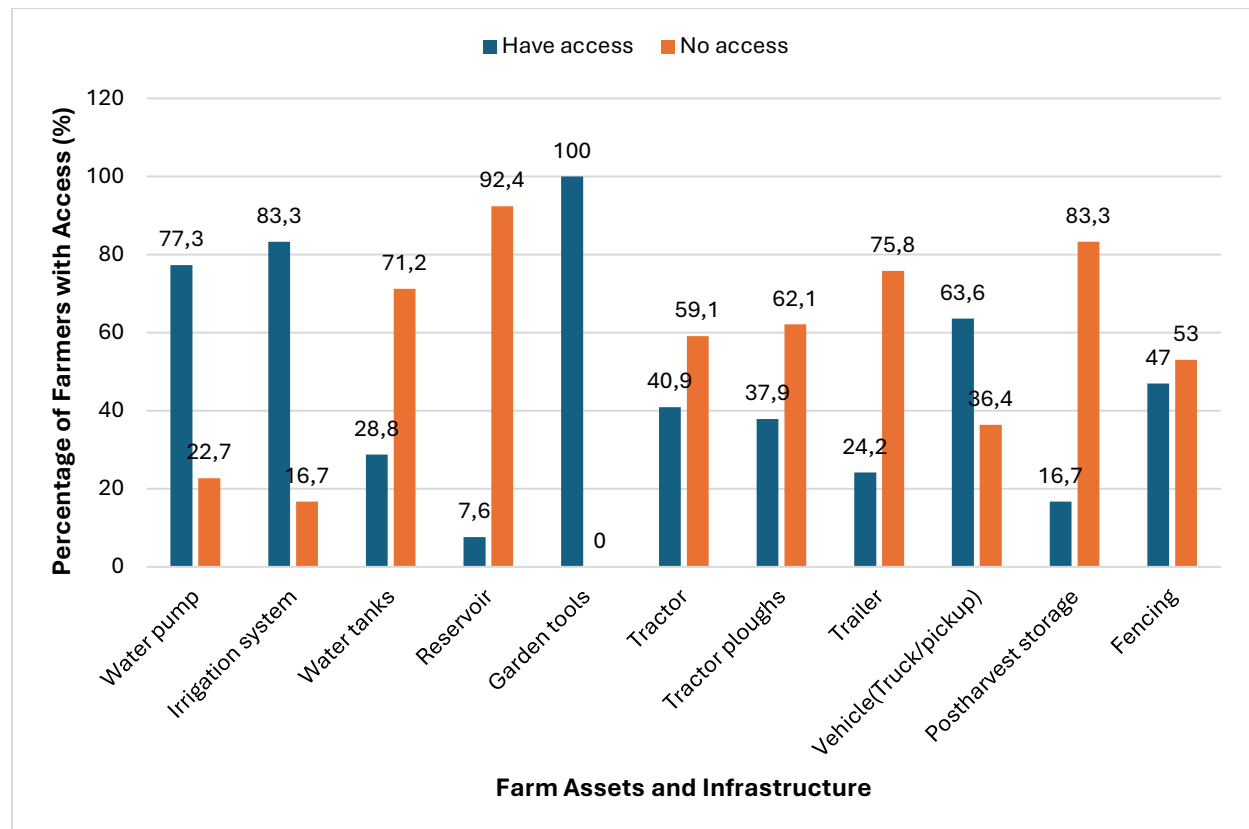


Figure 3.9: Ownership of farm assets and irrigation infrastructure among FLID farmers.

In terms of basic garden tools, 100% of the farmers have access to essential items, such as a hand hoe and wheelbarrow, which are vital for daily fieldwork. These results are consistent with studies done on South African smallholder farmers, both independent farmers and those in irrigation schemes (Malatsi et al., 2025). However, access to power tools and implements is relatively low, with ownership of tractors, ploughs, and trailers accounting for 40.9%, 37.9%, and 24.2%, respectively. The results suggest that farmers rely heavily on manual labour or hiring machinery for farm operations. Malatsi et al. (2025) reported a similar trend among farmers, with a few owning tractors. The low ownership of farm machinery may be attributed to the relatively

small landholdings (<10 hectares) among FLID farmers, which make it uneconomical to own farm machinery for their own use. Nonetheless, this provides an opportunity for developing suitable models for machinery hire services if it is possible to form farming clusters. On the contrary, 63.6% of the farmers have access to a vehicle (truck or pickup), suggesting that these farmers use their daily or home vehicles to operate on the farm to transport produce and inputs, while 36.4% have no access to vehicles. Figure 3.9 further reveals that only 16.7% of the FLID farmers have access to postharvest storage facilities. This suggests a high risk of post-harvest losses. The lack of storage facilities also exposes farmers to low prices common during harvest seasons. Similarly, the lack of proper fencing among 53% of respondents suggests they are vulnerable to theft and damage from stray animals. These factors match critical factors that led to failure among the Smallholder Irrigation Scheme (SIS) farmers in South Africa (Van Averbeké et al., 2011b, Van Koppen et al., 2017)

3.3.6. Farm operational and economic characteristics

Further descriptive analysis of the socio-economic characteristics of FLID farmers is shown in Table 3.1. According to Table 3.1, off-farm income averages R9,976.60 per month, ranging from R0 to R60,000. These results indicate a substantial spread in the survey group's economic conditions. Some households rely heavily on farming income, while others substantially supplement their income through off-farm activities. Off-farm income enhances the capacity to invest in irrigation infrastructure and soil improvement, contributing to the sustainability of FLID. This concurs with Materechera and Scholes (2021b) who demonstrated that grants, pensions, and other off-farm income often serve as capital for purchasing irrigation equipment, buying fuel, and supporting FLID investments.

Table 3.1: Descriptive statistics of continuous farmer and farmer characteristics

Variable	Mean	Std. Deviation	Minimum	Maximum
Non-farm income (R/month)	9976,6	15264,83	0	6000
Annual farm income (R)	129132,61	251326,764	0	1500000
Distance to market (km)	30,83	53,233	0	350
Transport cost to market (R/trip)	317,08	280,738	0	1900
Number of extensions visits per month	0,85	0,738	0	3
Share of produce sold (%)	47,54	35,843	0	95
Number of family labourers	0,86	1,036	0	4
Number of permanent labourers	2,15	2,099	0	10
Number of casual labourers	9,18	14,408	0	70
Family labour payment (R/month)	467,74	1016,001	0	3000
Permanent labour payment (R/month)	1974,84	1462,974	0	4500
Casual labour payment (R/day)	110	60,388	0	200

In terms of annual farm income, a noticeable variation is observed, with an average of R129,133 and some farms earning up to R1.5 million, indicating diverse profitability levels. This spread highlights differences in market access, farm management, and input use, which significantly affect farmers' ability to adopt and sustain irrigation technologies and soil fertility inputs. The results, as depicted in Table 3.1, indicate that the average market distance for the FLI farmer is 30.83 km, ranging from 0 km to 350 km, suggesting that farmers located far from markets may face higher transaction costs, affecting profits and their ability to sell fresh and good quality goods effectively, expose to longer travels and risk of product spoilage, while limiting access to timely inputs and buyers. These may reduce market competition, and '0 km' suggests that farmers sell their produce directly at their farm gates, which are likely to have walk-in customers. This means their market is conveniently located, making it easier for buyers to access fresh produce. Furthermore, the market distance is likely correlated with transportation costs to the market, with an average transport cost of R317 (R0-R1,900). These costs directly reduce farm profitability and can influence marketing decisions, such as selling locally rather than in distant urban markets.

There is significant variation in the percentage of produce sold among FLID farmers, ranging from 0% to 95%. On average, farmers sell approximately 47.54% of their produce, indicating a moderate market orientation. This is consistent with the main reason for farming shown in Figure

3.3, where about 35.2% practiced farming for income generation, whereas 10.1% and 32%. % of the farmers practiced farming for food security and home consumption, respectively. There is limited family labour involvement in farmer-led irrigation systems in the Vhembe district, with an average of 1 labourer per system (Table 3.1). This can be attributed to the low household size, as shown in Figure 3.2. A significant majority of FLID farmers (75.8 %) have a family size of 0–5 persons, consistent with demographic trends among middle-class families, who make up 50% of the FLID respondents in this study. As such, FLID farms rely heavily on hired labour, with the study reporting an average of two permanent labourers with a maximum of 10. The number of casual labourers ranged from an average of 9 to a maximum of 70, depending on seasonal or peak periods (Table 3.1). The mix of labourers reveals varying payment arrangements, where family labourers receive either R468 per month or none, indicating informal employment, while permanent labourers earn R1,975/month and casual labourers receive R110/day. This highlights the seasonal, labor-intensive nature of irrigation farming, where hired labour is crucial during peak workload periods, thereby affecting operational costs and productivity.

Market access and marketing arrangements

The majority of farmers have access to the market (86.4%), while 13.6% do not. The farmers use different market outlets as shown in Figure 3.10. The study reveals that the largest percentage of FLID farmers use on-farm and local sites (such as farm gates, roadsides, and pension pay points), accounting for 44.9%, followed by formal retail sites and institutions (such as supermarkets, cooperatives, contracts, and feeding schemes for schools and hospitals), accounting for 23.7% of farmers. The high percentage of FLID farmers at on-farm and local sites suggests that these farmers tap into informal markets and make most sales directly to consumers due to accessibility, reduced constraints on selling, such as distance, transport costs, poor road conditions, logistics, and quality requirements, and minimal infrastructure requirements. Similar findings on local site and on-farm dominance match Vhembe smallholder patterns, where farm gate and roadside preference exceed formal markets due to accessibility or low transport costs (Chikazunga and Paradza, 2013)

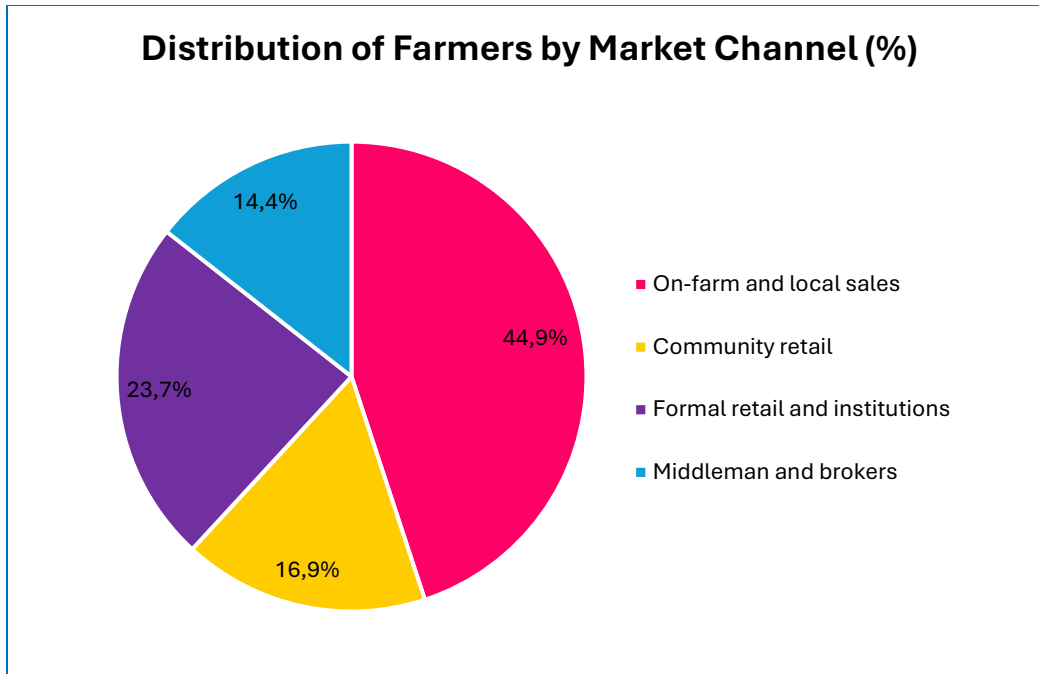


Figure 3.10: Market channels used by FLID farmers.

Community retail (including spaza shops, hawkers, and local farmers' markets) and middlemen and brokers had the lowest proportion, accounting for 16.9% and 14.4% respectively. The low preference for community retail, middlemen, and brokers was attributed to the relatively low prices these market channels offer. These sentiments from FLID farmers align with the findings of Van Koppen et al. (2017) and Chikazunga and Paradza (2013) hawkers and brokers buy low-priced bulk at local markets and are therefore shunned by farmers.

The findings indicate that access to formalised markets by FLID farmers may be derailed by inadequate support services and limited access to finance. High transport costs and low market prices are major barriers to access to formal markets. Both Chikazunga and Paradza (2013) and Baloyi (2010) reported that smallholder farmers in Limpopo province travel long distances to markets, incur high transport costs, and experience postharvest losses, which ultimately translates to low prices at markets. These findings emphasize that a farmer having access to markets doesn't imply that the market is effective or profitable.

3.3.7. Agricultural water management (AWM) practices (Irrigation systems and methods)

Figure 3.11 indicates that the majority of FLID farmers rely heavily on borehole water as their primary irrigation source, accounting for 63.6%, followed by rivers and spring water sources at 27.3% and 7.6%, respectively. According to Nesamvuni et al. (2022) Smallholder farmers prefer surface water due to their proximity to the rivers and the ease of access in Vhembe. However, unreliable rainfall and declining river flows have made groundwater a critical water source for irrigation.

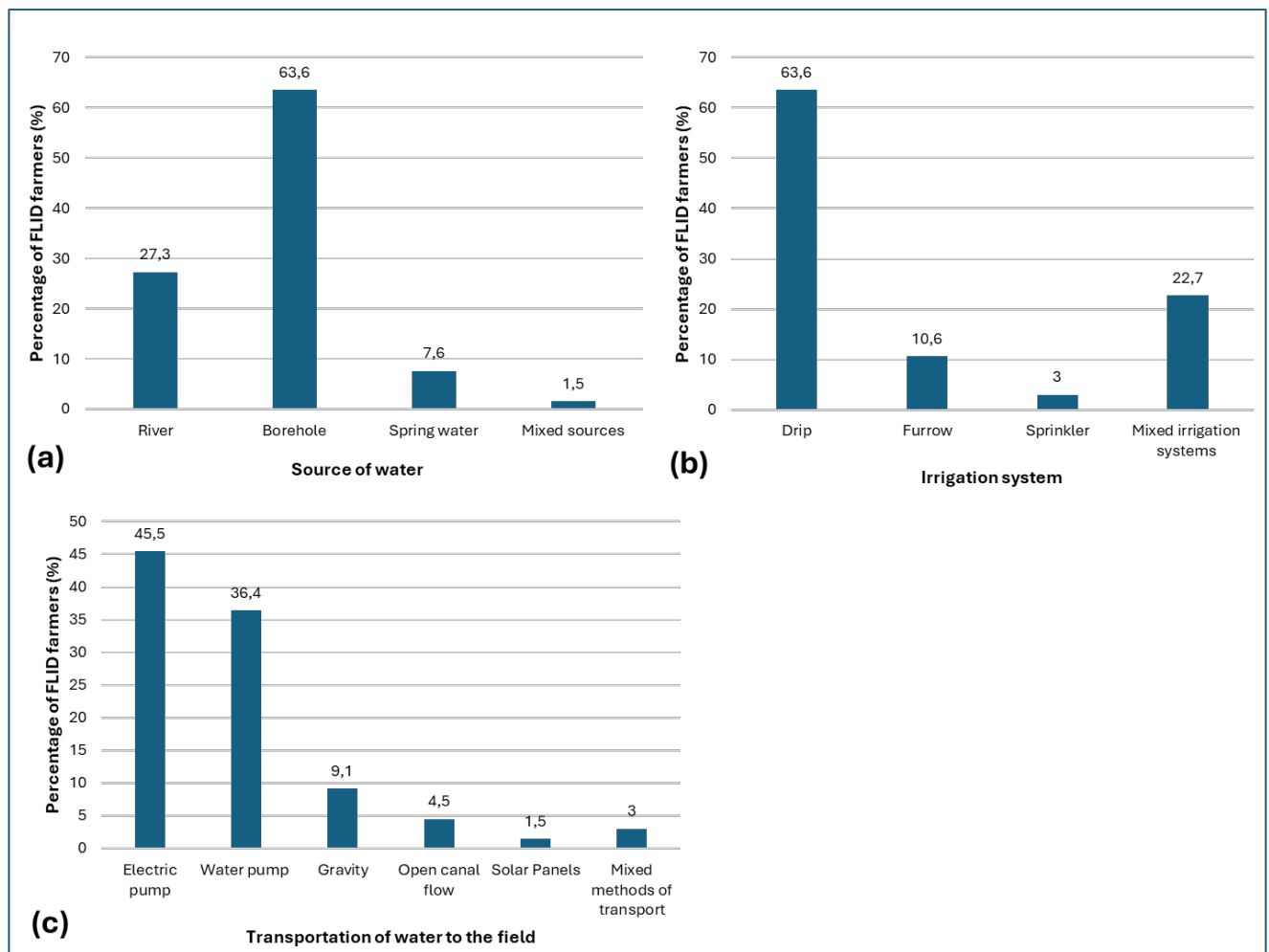


Figure 3.11: (a) Water source, (b) irrigation system types, and (c) water transport power among FLID farmers.

The findings from this study show that most FLID farmers prefer motorised pumping solutions for conveying water to their farms. Grid-tied electric pumps make up the majority at 45.5%, followed by diesel/petrol pumps at 36.4% and solar pumps at 1.5%. 9.1% and 4.5% of the farmers use gravity and open-channel flows, respectively, with 3% preferring mixed methods. The dominance of electric pumps may indicate extensive use of boreholes, whereas diesel/petrol pumps may be more popular among farmers who use river water sources due to their portability. The results in Figure 3.11 further present that the majority of FLI farmers use drip irrigation systems accounting for 63.6%, followed by farmers who prefer a combination of different irrigation systems, such as sprinkler and drip, or drip and furrow and/ or drip and flood irrigation systems, accounting for 22.7%, then followed by furrow irrigation system, accounting for 10.6%. Despite the significant preference for drip irrigation, FLID farmers highlighted that drip irrigation systems are expensive, prone to blockages, theft, and leaks, and difficult to maintain, leading to crop loss in some cases. The Irrigation system installation costs are high and show a highly significant difference among the FLID farmers surveyed. The average irrigation installation cost was R49,947 with a maximum of R350,000 (Table 3.2), indicating differential access to and investment in irrigation technology that influences irrigation practices and soil health.

Table 3.2: Descriptive statistics for water management parameter characteristics

Variable	Mean	Std. Deviation	Minimum	Maximum
Monthly water payment (R)	27,95	104,95	0	600
Willingness to pay for water (R/month)	141,07	318,438	0	2000
Water expenses (R/month)	4634,62	9095,967	0	40000
Average irrigation duration (hrs)	4,02	3,44	1	24
Irrigation system installation cost (R)	49947,17	62072,01	0	350000
Distance from water source to field (m)	99,19	178,851	1	700
Casual labour payment (R/day)	110	60,388	0	200

The findings of this study imply that a majority of farmers do not pay for water, particularly those who abstract water from rivers or their own boreholes. The average monthly water payment is R27.95, with some farmers paying nothing and others paying up to R600. This range indicates variability in access to water infrastructure and water rights. The FLID farmers indicated their willingness to pay for water, with suggested monthly payments ranging from R0 to R2000.

However, this is below their current water expenses, which range from 0 to R40000, with an average of R4,634.62. The water expenses include operational costs beyond direct payments, such as electricity bills, pump fuel, and maintenance of water infrastructure. The high-water expenses are consistent with the long irrigation hours, averaging approximately 4 hours per day and reaching a maximum of 24 hours. The variation in irrigation periods may be attributed to differences in land size and irrigation methods. Most farmers use drip irrigation, which takes longer to reach field capacity, whereas larger farms may irrigate different blocks sequentially throughout the 24-hour period. The high-water cost may also be attributed to pumping costs, whether from boreholes or river sources. The average distance from the water source to the cultivated field is 99 meters, but it ranges widely, up to 700 meters. The proximity to water sources, particularly rivers, may result in lower costs. However, a borehole source may still incur high water pumping costs despite being located within the cultivated area.

Visual Assessment showing different water sources, water transport modes, and irrigation systems

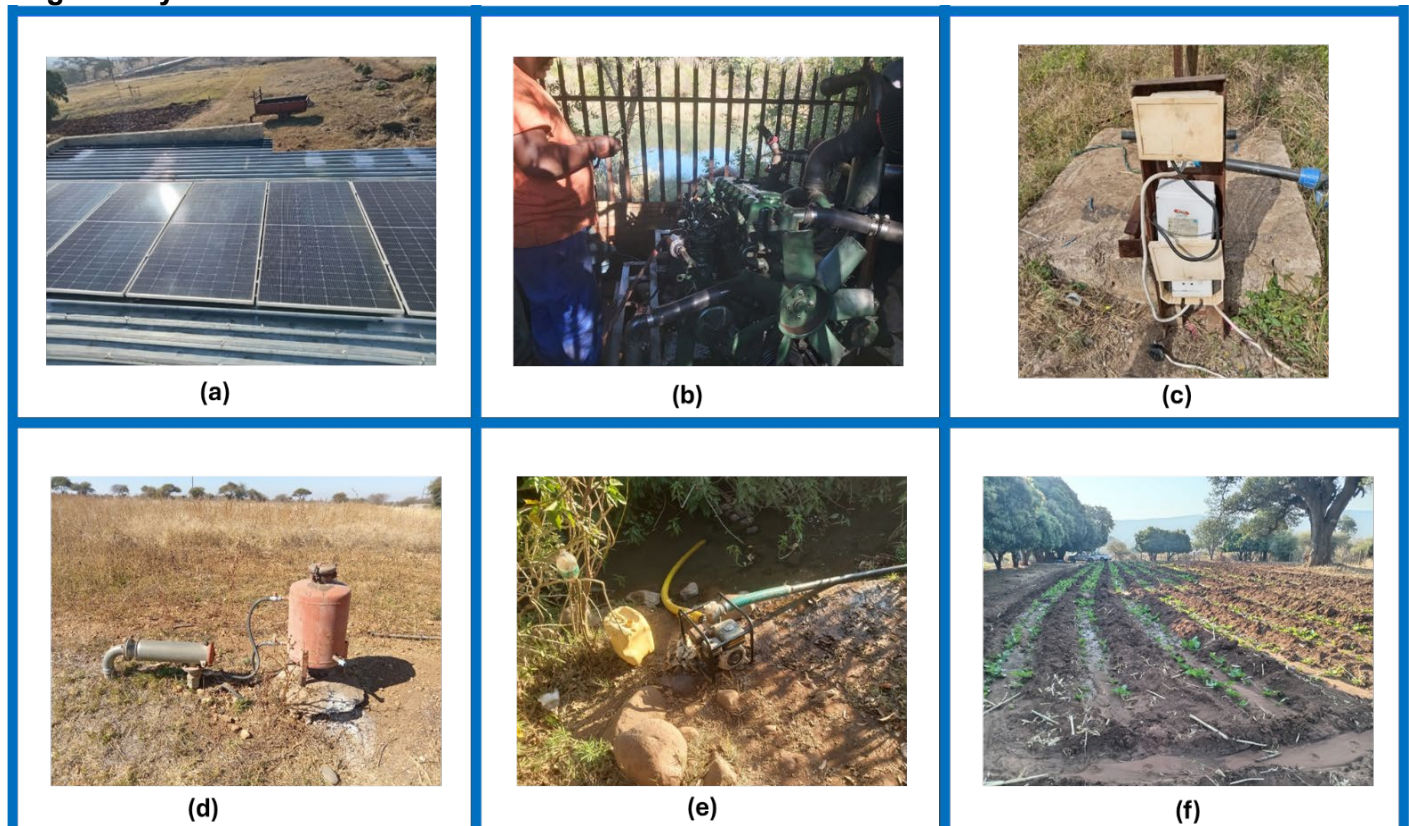


Figure 3.12: (a) Solar panels, (b) Water pump by diesel, (c & d) electric pump, (d) Water pump by petrol, (e) Gravity.

Water User Association

Figure 3.13 illustrates the percentage distribution of FLID farmers' knowledge and willingness to join Water User Associations (WUAs), as well as their current water payment practices and willingness to pay for water services. The study reveals a significant knowledge gap, as 81.8% of the FLI farmers are unaware of WUAs and their implications. These findings suggest a poor link between water management bodies, extension services, and FLID farmers, which limits farmers' access to water licenses. A similar observation was made by (Van Averbek, 2013, Nedombeloni, 2023) where limited extension outreach and poor WUA linkages exclude informal FLID farmers from licensing information. Despite limited knowledge of WUAs, 53% of FLID farmers expressed interest in joining WUAs to achieve effective water use on their farms and to access opportunities provided by WUAs.

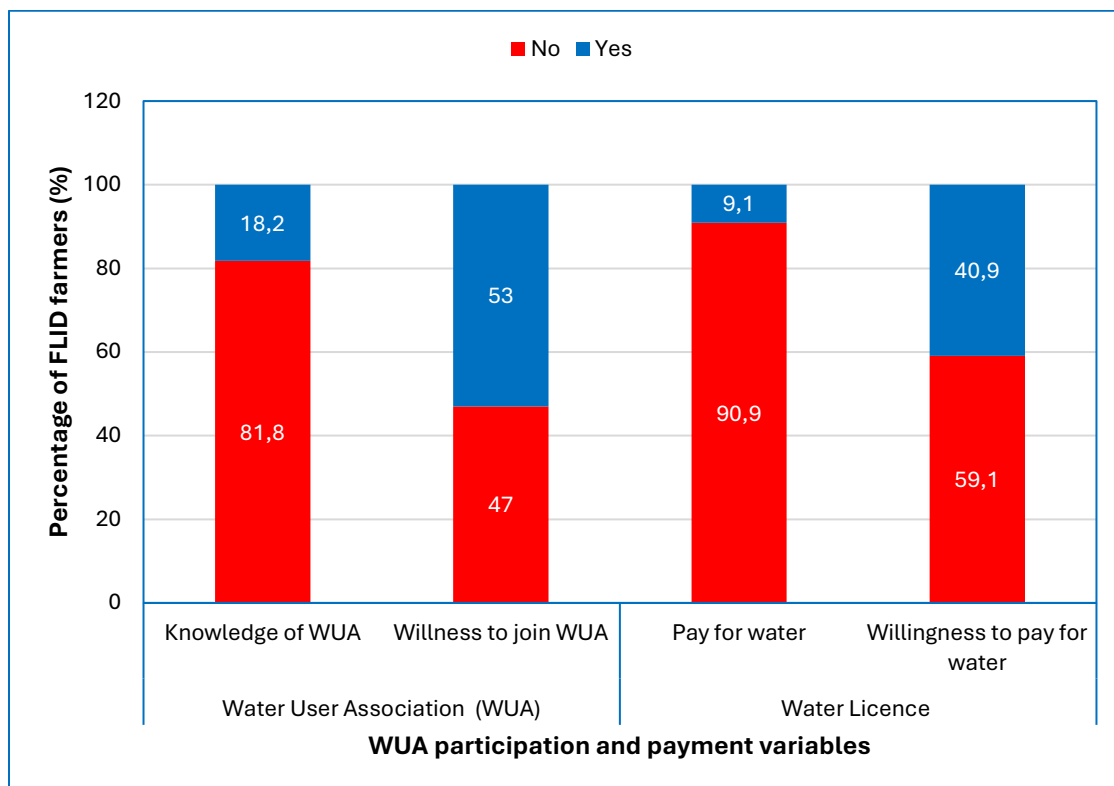


Figure 3.13: Knowledge, participation, and water payment behaviour relating to WUAs and licensing.

The lack of water licensing hinders farmers from receiving government support, as it is one of the key requirements to access a variety of government support. Only 9.1% of the farmers pay for a water licence, whereas 90.9% indicated they do not see the benefits of having one. However, 59.1% of the FLI farmers are willing to pay for water to be eligible for government support. Nevertheless, 40.9% of the farmers, particularly those using their own boreholes, remain unwilling to pay for water licences due to the already high water-related expenses, such as electricity and petrol. They also view the water licensing process as expensive and overly bureaucratic.

3.3.8. Farmers' knowledge constrains perceptions in water-saving practices.

Figure 3.14 illustrates the varying knowledge levels of FLID farmers regarding water-saving practices through soil and water management, which are essential for a sustainable farmer-led irrigation development system. The results show that FLID farmers possess extensive knowledge of drip irrigation and irrigation scheduling, with 68.2% and 50%, respectively, and only 13.6% and 6.1% having no knowledge. These findings suggest that FLI farmers have the capacity to use water efficiently and conserve water, aligning with a study by Joseph et al. (2021), which found that farmers prioritise these irrigation management practices, such as water harvesting and drought-resistant crops, to increase yield under drastic climatic change scenarios.

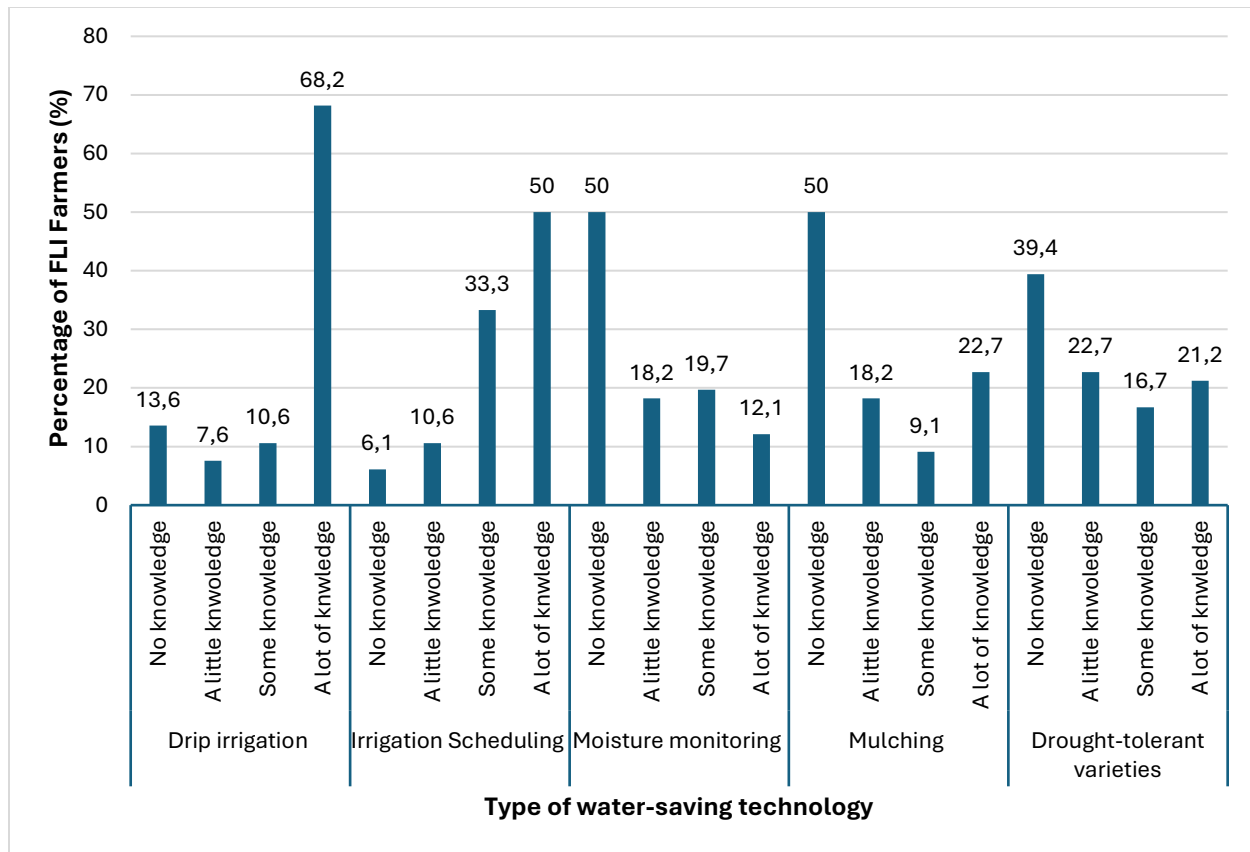


Figure 3.14: Farmers' knowledge of water-saving technologies

However, 50% of farmers lack knowledge of moisture monitoring and mulching practices. This may be due to the lack of equipment, such as tensiometers, for monitoring. This suggests that the irrigation scheduling done by the farmers is arbitrary and not based on soil moisture data. Similarly, 39.4% of the farmers reported a lack of knowledge about drought-tolerant crops, indicating a need for more information on resilient crop varieties to mitigate the impacts of climate change. As such, improving farmer training and extension services, with a focus on practices such as moisture monitoring, mulching, and the use of drought-tolerant varieties, could significantly enhance the quality of produce and climate resilience for the FLID farmers in the Vhembe region.

Despite the farmer's knowledge of water-saving technologies, their adoption remains constrained, primarily due to limited access to these technologies, high implementation costs, limited knowledge, and inadequate government support (Figure 3.15). The results showed that a significant number of FLI farmers, accounting for 77.3%, consider limited access to technology a very big problem, with only 12.1% considering it a problem, followed by 7.6% who don't see it as

a problem, and lastly, 3% who identify it as a small problem. These findings suggest that the majority of farmers encounter constraints in accessing equipment, such as tensiometers, to monitor soil moisture due to limited knowledge, a lack of awareness, inadequate financial support, and insufficient training, which aligns with the constraints faced by Vhembe smallholder farmers, where extension officers often fail to support independent farmers (Serote et al., 2023b). Similarly, a lack of knowledge about some water-saving methods is also considered a key constraint, accounting for 71.2% as a very significant problem and 18.2% as a problem. Additionally, FLI farmers identified high implementation costs and a lack of government support as significant problems, accounting for 78.8% and 60.6%, respectively, findings that align with the study by Serote et al. (2023), which found cost barriers among farmers in Vhembe. These factors were also identified by other farmers as problems, accounting for 19.7% and 16.7%, respectively. Regarding the cost of water-saving methods, the majority of farmers reported it as very expensive, accounting for 71.2%. This was followed by farmers who identified the cost as expensive (15.2%) and reasonable (12.1%), respectively. A small fraction of farmers considered the cost as relatively cheap, accounting for 1.5%.

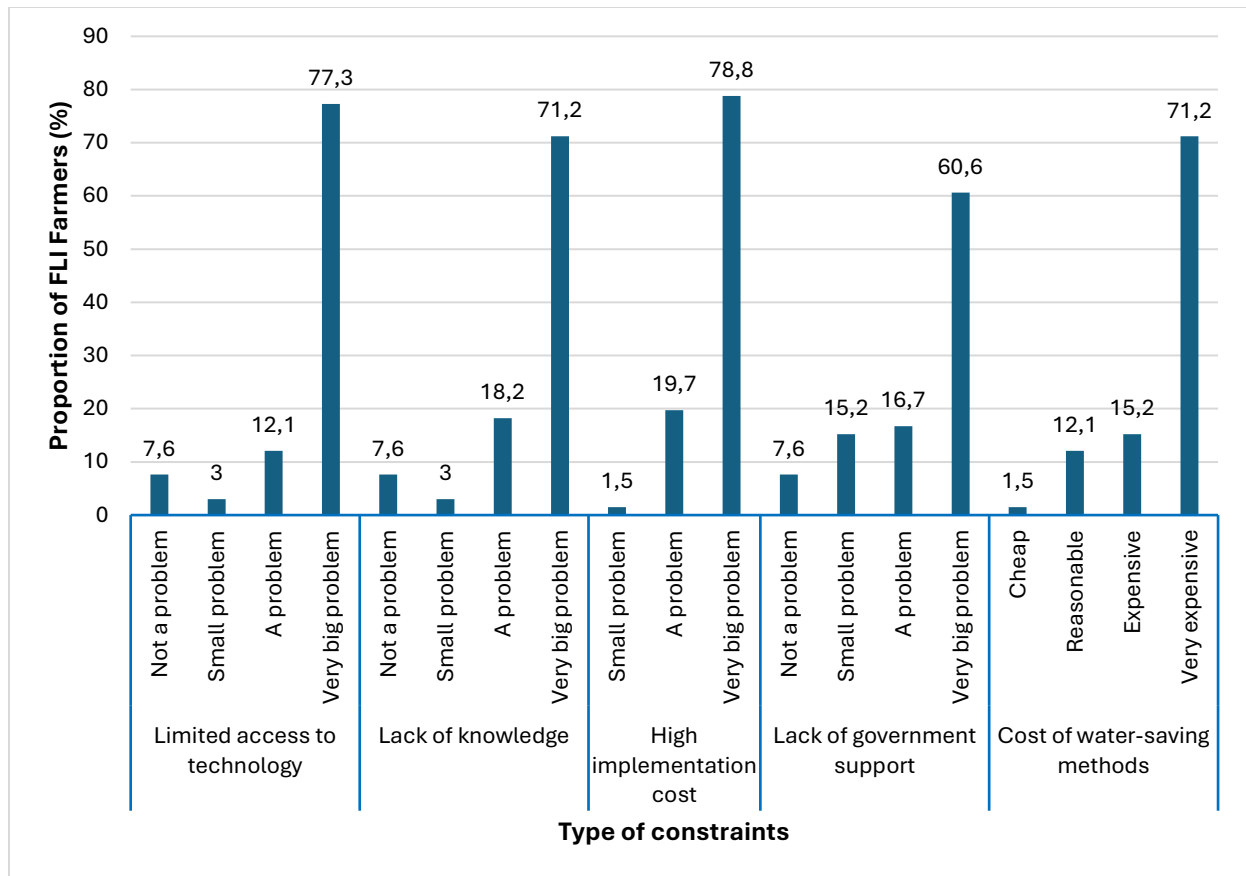


Figure 3.15: Perceived Constraints to Using Water-Saving Technologies

3.3.9. Climate change impact and adaptation

The impacts of climate change on water availability, crop yields, and adaptation measures are depicted in Figure 3.16. Regarding water availability, the majority of farmer-led irrigation farmers (33.3%) reported experiencing heat waves on hotter days and nights. Additionally, 12.1% of the farmers observed both lower river levels and borehole drying. These findings align with a study by Shoko Kori et al. (2024) that reported rising temperatures, heatwaves, reduced rainfall, which is unpredictable and unreliable, and decreased river flow in the Thulamela municipality in the Vhembe district. However, 31.8% of the farmers reported no change noticed in the water availability, and only 7.6% and 3% reported less rainfall and heavy rainfall, respectively. This indicates that climate change is experienced differently by FLID farmers, who use irrigation to supplement rainfall variability.

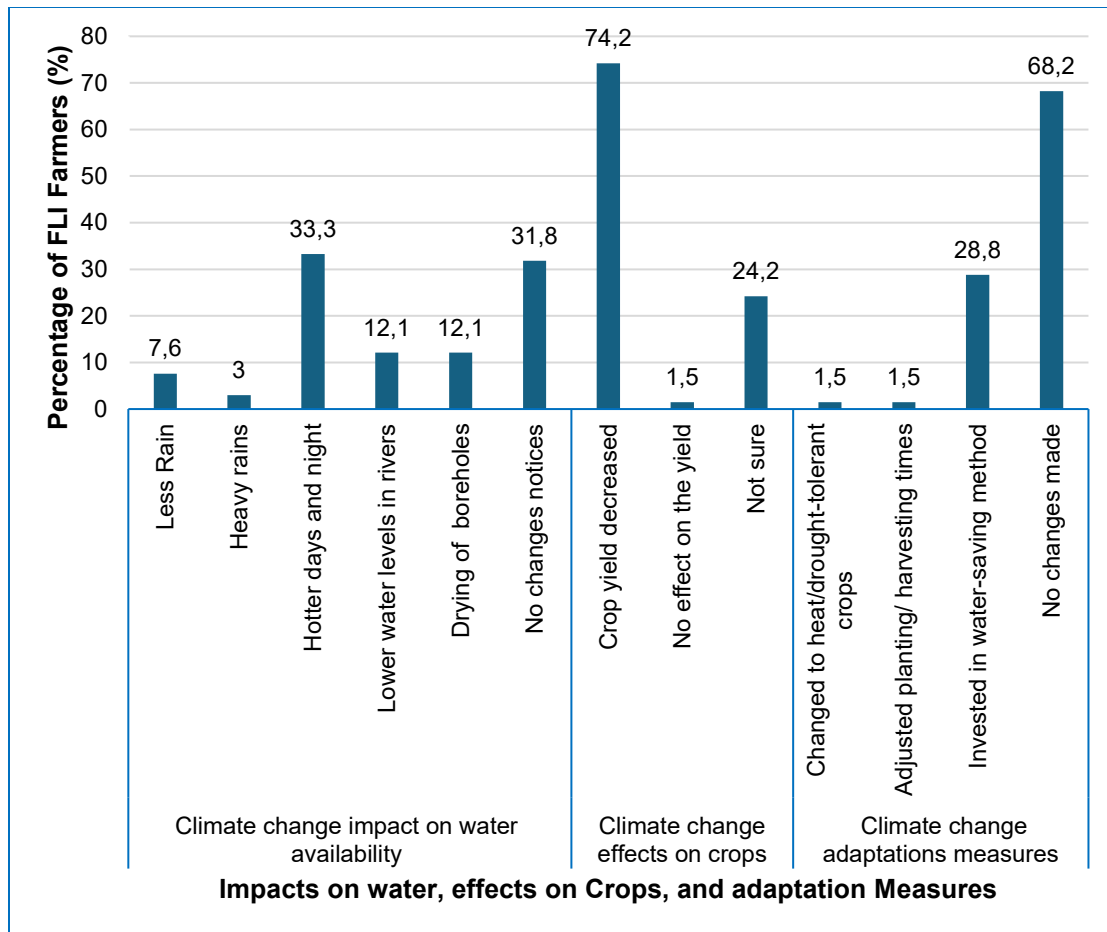


Figure 3.16: Farmers' Perceptions of Climate Change Impacts and adaptation Measures adopted by FLI farmers in Vhembe District

Regarding the impact of climate change on crops, 74.2% of respondents reported a drastic decline in crop yields due to high temperatures (heatwaves and frost) and reduced rainfall, particularly among farmers who rely on rivers as a source of water and rainfall as a supplement. This aligns similarly with studies in South Africa, including Vhembe, indicating that changing rainfall, more long-term heat waves, and more droughts have huge impacts and significantly reduce crop yield (Shoko Kori et al., 2024). However, 1.5% reported no effect on crop yield, and 24.2% reported being uncertain about the impact, and this could be due to differences in management practices, crop diversification, and access to sufficient irrigation water, which align with a study by (Joseph et al., 2021) that reported that such factors improve resilience against climate shock among citrus farmers.

Despite the significant impact of climate change on water availability and crops, the majority of FLID farmers did not make any changes to adapt to these conditions, accounting for 68.2%, which

suggests limited resources, a lack of institutional support, or a lack of knowledge on adaptive measures, even though they are aware of climate risks which is similar to the findings reported by Shoko Kori et al. (2024) in the Vhembe district. As such, there's a need for more informed support and accessible, adaptable measures for crop production and sustainable farmer-led irrigation. Only a small fraction of FLID farmers changed to heat- or drought-tolerant crops or adjusted their planting or harvesting times, accounting for 1.5%. Nonetheless, 28.8% of the FLI farmers reported investing in water-saving methods, such as drip irrigation.

3.3.10. Institutional support, access to information, training, and governance

Access to institutional support services, mainly provided by local government support structures, is shown in Figure 3.17. The results indicate that a majority (72.7%) of the farmers have access to agricultural extension services that facilitate their participation in various training programs, such as general agricultural training (66.7%), irrigation training (65.2%), and water management training (65.2%). Although most farmers indicated they have extension officers responsible for their areas who assist them, they do not receive sufficient extension support due to limited visitation. The farmers reported an average of just 1 visit per month, with a few reporting up to 3. The FLID farmers alleged favoritism toward some farmers, leading to a disparity in the number of visits. Furthermore, the farmers complained that the extension support focused more on farmers in public irrigation schemes than on independent farmers. Similar concerns about inadequate extension staff and bias towards formal state irrigation schemes were reported by Van Averbeké (2013). In addition, FLID farmers indicated that extension officers repeatedly bring the same information, offer poor services (technical advice), and have inadequate market knowledge. These limitations could significantly affect productivity and farm performance by hindering knowledge transfer in management practices and disease detection, as well as access to crucial agricultural insights and the adoption of new innovations.

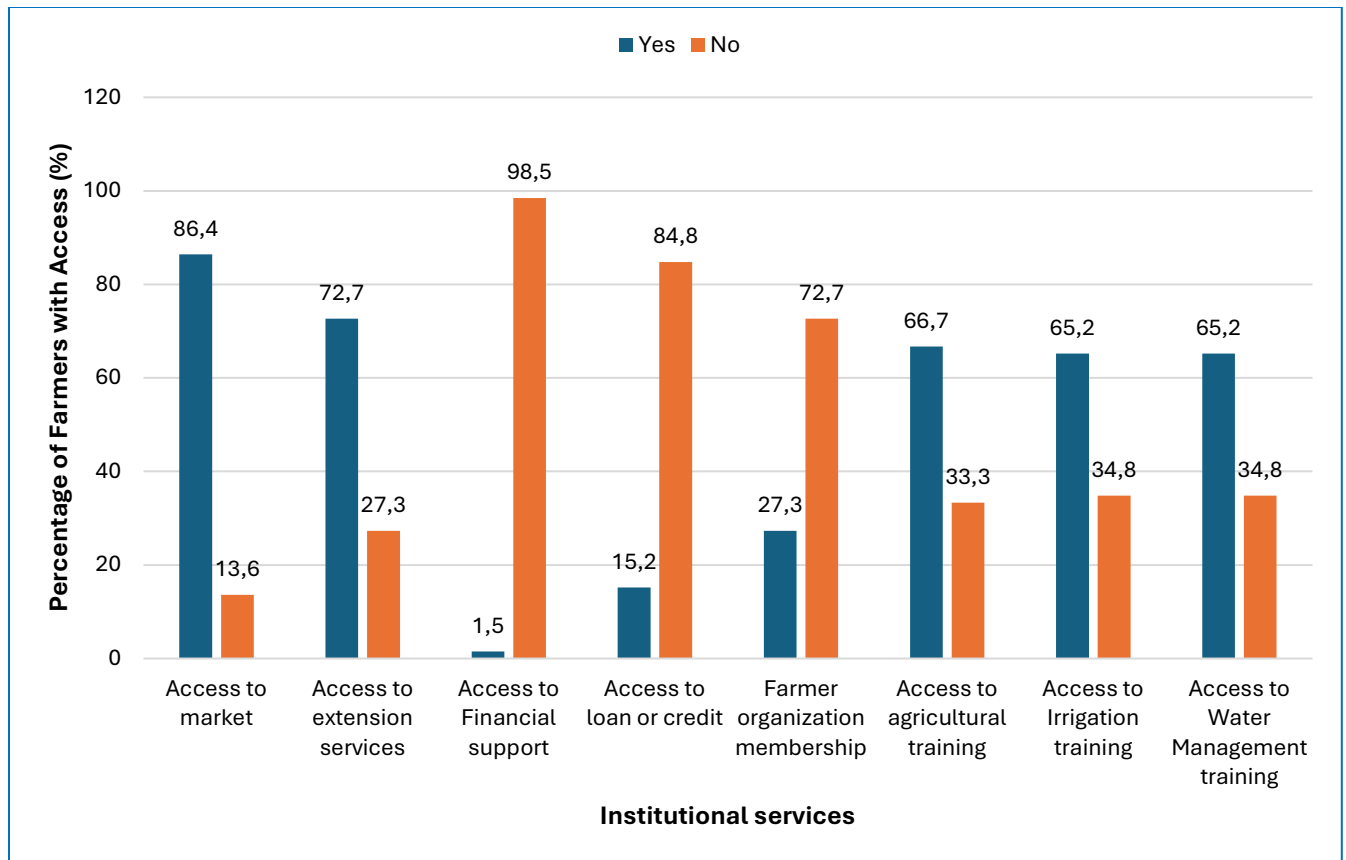


Figure 3.17: Institutional services access by FLI farmers (extension, finance, training) in Vhembe district

The study reveals a significant gap in access to financial support, with only 1.5% of farmers having access to financial support (grants, funding, and subsidies). Similarly, only 15.2% of FLID farmers have access to loans or credit. The farmers indicated that they rely on family members and informal moneylenders for loans and credit. The lack of support from formal lending/credit institutions may be due to insufficient collateral to secure such loans/credit. None of the FLID farmers had title deeds to their farms, which makes it impossible to use their land as security to secure credit from formal financial institutions. The lack of financial support and access to loans or credit suggests a significant limitation on farmers' ability to invest in irrigation infrastructure and improved soil and water management practices that would enhance their productivity and profitability. Moreover, the results show that only 27.3% of the farmers are members of farmers' organizations (Tshilwavhusiku Vegetable Growers' Association). This suggests that FLI farmers operate independently, without formal peer connections, which ultimately hinders knowledge transfer and access to resources, inputs, and training.

3.3.11. Advanced statistical analysis on factors affecting performance

Principal Component Analysis (PCA)

The Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy, which indicates that the PCA was appropriate for analysis, was 0.605 (Table 3.3). This value suggests that the set of soil management practices, irrigation management practices, FLID's farmers' perception of land conditions, and knowledge of water-saving technologies variables shares enough common variance to justify using PCA (Table 3.3). In addition, Bartlett's test of sphericity is highly significant ($\chi^2 \approx 298.6$, $p < 0.001$, $df = 153$) in Table 3.2 hence, the PCA was good for measuring these variables.

Table 3.3: KMO and Bartlett's Test of Sphericity

Measurements	Values
Kaiser–Meyer–Olkin (KMO)	0,605
Bartlett's Test (χ^2)	298,6
Degree of freedom (df)	153
Sig. (p-value)	<,001

The use of PCA on soil and water management practices, land condition perception, and farmers' knowledge of irrigation technologies yielded six components with eigenvalues greater than 1 in the total variance table (Table 3.4), collectively accounting for approximately 63.8% of the total variance in the original variables. The first component explains approximately 17.6% of the variance, the second 14.3%, and the remaining four components account for 9.8%, 8.4%, 7.3%, and 6.2%, respectively.

Table 3.4: Total Variance Explained by Retained Principal Components

Component	Eigenvalues	%Variance	Cumulative (%)
PC1	3,174	17,635	17,635
PC2	2,578	14,324	31,958
PC3	1,78	9,892	41,85
PC4	1,522	8,456	50,306
PC5	1,317	7,315	57,621
PC6	1,121	6,225	63,846

The rotated component matrix shown in Table 3.5 below reveals a clear, interpretable pattern of loadings grouped into six conceptual factors. These six PCAs indicate that the PCA effectively condenses a wide range of soil and water management practices and knowledge variables into a small number of meaningful dimensions that accurately reflect the FLID context.

Component 1 is dominated by FLID farmers' knowledge of water-saving technologies, with strong positive loadings for mulching (0.771), efficient Irrigation (0.741), soil moisture monitoring (0.627), and drought-resistant crops (0.561). This component reflects farmers who are well-informed about soil and water-saving technologies and possess climate-smart knowledge, making them more likely to apply conservation practices on their farms. This knowledge is a key driver of productivity in water-scarce regions, such as the Vhembe district. Component 2 is best described by drip Knowledge (0.735) and irrigation duration (0.514). This component reflects farmers who are familiar with more advanced irrigation systems, longer irrigation events, indicating higher irrigation frequency and more intensive use. This further suggests that the farmer may have better knowledge of their farm and be confident in their soil.

Component 3 groups Drainage, Water Holding Capacity (WHC), and soil nutrient supply, where it shows high loading for drainage (0.809) and WHC (0.781), and a substantial loading for nutrient supply (0.545). This component shows the soil hydraulic and fertility functionality, or the perceived soil water storage (drainage and WHC) and productivity potential, crucial to response under irrigation. Farmers scoring high on this factor view their soils as well-drained, with good water-holding capacity and nutrient availability. In contrast, Component 4 is strongly defined and dominated by water source and pump type, accounting for 0.746 and 0.794, respectively. This

indicates a clear infrastructure dimension governing access to irrigation water and further suggests that farmers with higher scores for component 4 have more developed water sources and irrigation pumping equipment.

Component 5 loads mainly and strongly on weeds (0.648), salinity (0.657), and nutrient supply (0.558), reflecting production constraints and soil limitations regardless of management practice, and component 6 is driven by soil management practice (0.784), cropping systems (0.672), and a moderate loading from irrigation method, accounting for 0.417, reflecting long-term soil productivity strategies. Tillage practice and soil resilience perception were included in the PCA but are not presented as defining variables in this table because they did not load strongly (≥ 0.50) on a single component after Varimax rotation. However, these variables contributed to the overall PCA solution and factor scores but were excluded from component labelling to preserve interpretability.

Table 3.5: Rotated Component Matrix (Varimax Rotation)

Variable	Component					
	PC1	PC2	PC3	PC4	PC5	PC6
Mulching knowledge	0,771	-0,087	0,085	0,007	0,041	0,063
Efficient irrigation knowledge	0,741	0,292	-0,252	0,009	-0,051	-0,15
Soil moisture knowledge	0,627	0,12	0,141	-0,19	-0,307	-0,248
Drought-tolerant crops knowledge	0,561	-0,408	-0,111	-0,108	0,346	0,149
Drip irrigation knowledge	0,334	0,735	-0,076	-0,042	0,038	-0,155
LN irrigation duration	-0,032	0,514	0,372	-0,02	0,012	0,042
Drainage (land condition)	0,131	0,17	0,809	0,136	-0,119	-0,006
Water holding capacity (WHC)	-0,144	0,309	0,781	-0,006	-0,059	-0,082
Soil nutrient supply (land condition)	-0,03	-0,264	0,545	0,058	0,558	-0,038
Pump type	-0,041	0,125	-0,064	0,794	0,13	0,112
Water source	-0,191	0,003	0,32	0,746	0,029	-0,181
Weeds (land condition)	-0,13	0,049	-0,058	0,25	0,648	0,075
Salinity (land condition)	0,069	0,026	-0,068	-0,097	0,657	-0,085
Cropping system practice	-0,179	-0,265	-0,162	-0,209	0,24	0,672
Soil management practice	0,042	0,021	0,015	0,053	-0,232	0,784
Irrigation method	-0,314	0,239	0,033	-0,511	0,201	0,417

PC1: Soil & Water-Saving Knowledge, PC2: Irrigation Duration & Technology Knowledge, PC3: Soil Water Storage Capacity, PC4: Irrigation Infrastructure Access, PC5: Soil Degradation Constraints, and PC6: Soil Fertility & Cropping Management.

Multiple Linear Regression (MLR)

The multiple linear regression (MLR) model, using the six PCA scores and the irrigation training indicator as predictors of log farm income, yields an R^2 of 0.365 and an adjusted R^2 of 0.248. This indicates that about 36.5% of the variation in irrigation farm income is explained by the combined

effects of farmers' knowledge of water-saving technologies, land conditions, soil and water management practices, and irrigation training. The overall model was statistically significant ($p < 0.05$), confirming that the predictors, taken together, contribute meaningfully to explaining variation in farm income. In addition, the Durbin–Watson statistic, with a value of 2.26, suggests no serious autocorrelation in the residuals.

Table 3.6: Multiple Linear Regression Model Summary

Statistic	Value
R	0.604
R ²	0.365
Adjusted R ²	0.248
F-statistic	3.123
Sig. (p-value)	0.011
Durbin–Watson	2.263

This section presents the multiple linear regression results and further discusses variables found to be significant in affecting the performance of FLID systems, where farm income is primarily influenced by knowledge-based and operational irrigation factors (as depicted in Table 3.6). Among the predictors, only PC1, PC2, and irrigation training show statistically significant associations with log farm income, while the other components are not significant ($p > 0.05$), as shown in Table 3.7.

The component representing integrated soil and water conservation knowledge and practice (PC1) was statistically significant ($p < 0.05$), with a positive coefficient ($\beta \approx 0.374$), indicating that farmers with stronger water-saving and soil-conserving knowledge and practices tend to earn higher farm income. This further suggests that these farmers possess extensive knowledge of soil and water management, enabling them to increase productivity on their farms. This could be attributed to their frequent presence on the farm, higher education levels (tertiary level mentioned above), and greater experience. This is supported by empirical evidence from Tanzania and Ethiopia which indicate that the adoption of soil and water conservation technologies improves

yields, income, and food security by reducing erosion and drought risk, as well as enhancing water use efficiency (Manda et al., 2023, Adimassu et al., 2017).

Similarly, the study also uncovered that the irrigation capacity and scheduling factor (PC2) has a statistically significant effect ($p < 0.05$), and a positive, significant coefficient ($\beta \approx 0.319$) impact on the performance of FLID farmers, suggesting that more advanced systems and longer, controlled irrigation events are associated with higher income. In this component, higher scores are driven by knowledge of drip irrigation and longer irrigation durations, which is consistent with drip systems applying small amounts of water over extended periods, helping farmers cope with the hotter day and night conditions reported in the Vhembe District in the descriptive analysis above. This result aligns with studies on smallholder irrigation in sub-Saharan Africa, which report that access to reliable irrigation water and appropriate technologies increases farm income and household welfare through higher cropping intensity, improved yields, and greater resilience to climate variability (Manda et al., 2023, Jiba et al., 2024). However, Mnkeni et al. (2010) reported that the income impact of irrigation technology can be constrained by high operating costs, weak markets, and inadequate maintenance, indicating that technology and longer irrigation alone are insufficient without supportive institutional and economic support.

In contrast, irrigation training has a significant negative association with farm income ($\beta = -0.298$, $p = 0.037$), indicating that, after controlling for management and land conditions, farmers who reported receiving irrigation training earned lower farm incomes than those without training, possibly reflecting programs that target training towards more resource-constrained producers. This could be due to farmers receiving the same generic information, as mentioned previously. Alternatively, these farmers may not be able to afford to implement water-saving technologies even after receiving the training. Since smallholder irrigation development in South Africa often prioritizes poorer, more constrained farmers and underperforming schemes for training and support, trainees typically start from a lower income and face more severe production challenges. The remaining components, PC3 (Soil Water Storage), PC4 (Irrigation Infrastructure), PC5 (Soil Constraints), and PC6 (Soil Fertility Management), were not significant ($p > 0.10$), implying no clear independent effect on farm income once the other factors are controlled for.

Table 3.7: Regression Coefficients for PCA Scores and Training

Predictor	Standardised β	t	p-value	Effect
PC1: Soil & Water-Saving Knowledge	0.374	2.846	0.007	Positive
PC2: Irrigation Duration & Knowledge	0.319	2.370	0.023	Positive
PC3: Soil Water Storage	-0.038	-0.290	0.773	NS
PC4: Irrigation Infrastructure	0.074	0.564	0.576	NS
PC5: Soil Constraints	-0.106	-0.808	0.424	NS
PC6: Soil Fertility Management	-0.200	-1.535	0.133	NS
Irrigation training	-0.298	-2.159	0.037	Negative

Integrated Performance Analysis: Fishbone diagram

Figure 3.18 illustrates an integrated performance analysis using a fishbone diagram, providing a holistic view of the interconnected factors that lead to the inefficient performance of FLID in the Vhembe district. The study identified 37 causal sub-factors and categorized them into 6 key thematic factors: institutional & policy support; infrastructure and irrigation technology; water management practices; economic and market factors; farmer characteristics and social factors; soil and land management; and environmental and climatic conditions. The Root Cause Analysis (RCA) synthesizes the findings from the quantitative analysis and links them to broader management, policy, and socio-economic challenges that affect FLI performance.

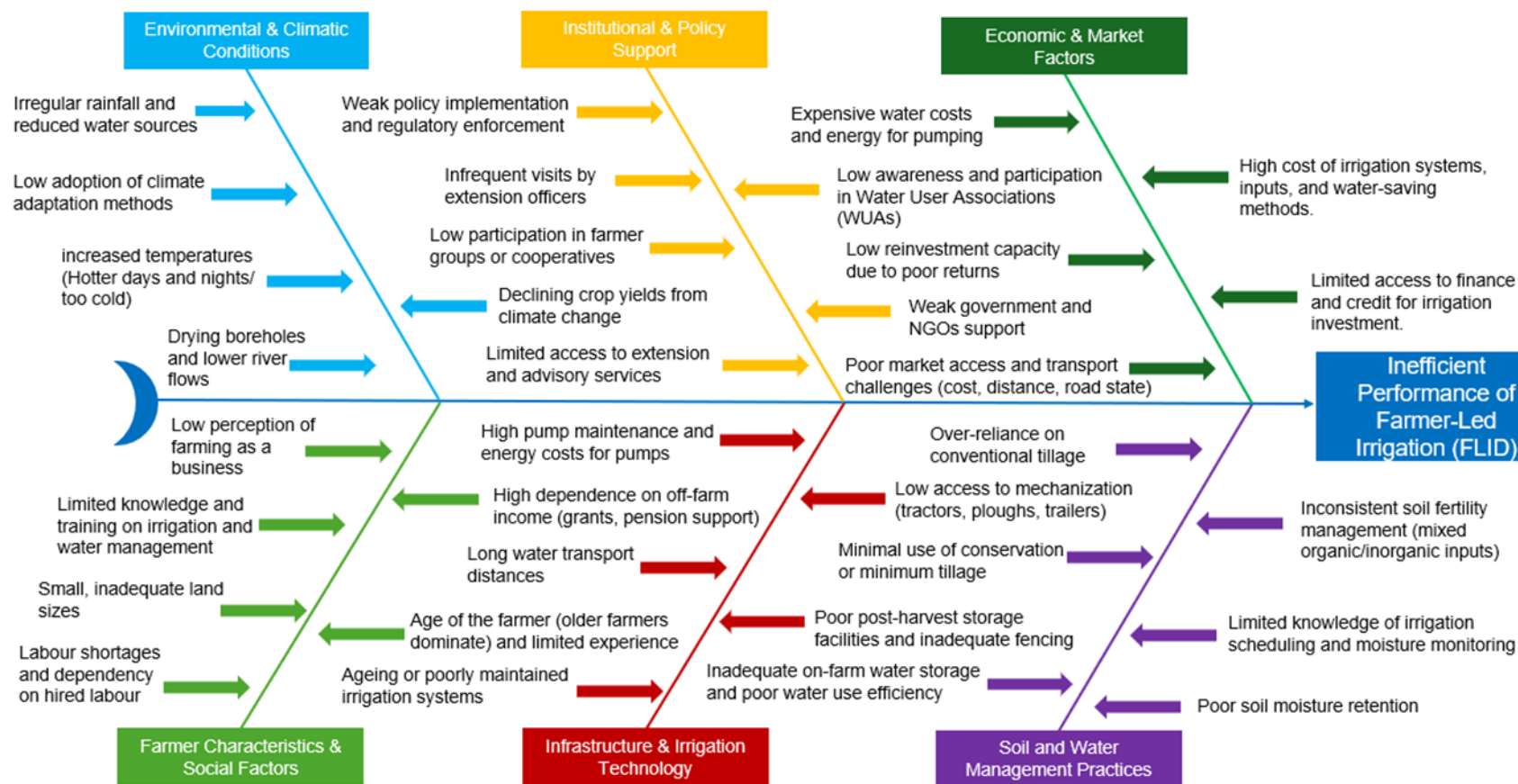


Figure 3.18: Fishbone diagram of factors influencing the performance of FLID in Vhembe District.

The economic and marketing factors were identified as the drivers for inefficiency in FLID systems. These economic and market constraints include high implementation costs (such as those for irrigation systems, inputs, and energy), limited access to finance and credit, poor market access, and transport challenges, as well as low reinvestment capacity due to poor returns, all of which contribute to the low sustainability of the FLID system.

The soil and water management practices were identified as another set of drivers with technical impact, such as inadequate on-farm water storage and poor water-use efficiency, limited knowledge of irrigation scheduling and soil moisture monitoring, and over-reliance on conventional tillage with minimum use of conservation or minimum tillage, leading to inefficient FLID performance.

Institutional and policy support were identified as intermediate, consisting of six subfactors, namely weak government and NGOs support, low awareness and participation in WUAs, limited access to extension and advisory services, low participation in farmer groups or cooperatives, infrequent visitation by extension officers, and weak policy implementation and regulatory enforcement. Without institutional support, farmers tend to be isolated and less innovative, and declining yields due to climate change result from factors such as poor participation in farmers' groups and limited knowledge of government programs.

Infrastructure and irrigation technology-operational tools, such as poor post-harvest storage facilities, lack of fencing, limited access to mechanization, high pump maintenance and energy costs, long water transport distances, and aging or poorly maintained irrigation systems, also affected the efficiency of the FLID system. These analyses align well with studies done in irrigation schemes in Vhembe, where limited infrastructure results in lower yields and higher operating costs, leading to frequent post-harvest losses.

The farmer characteristics and social factors were the fifth group of causal factors contributing to inefficiency in the FLID system. The majority of the farmer-led irrigation farmers were older, heavily depending on off-farm income sources (such as grants), and had limited knowledge and training on AWM practices. They had small farms and faced labour shortages, leading to reliance on hired labour. Additionally, they had a low perception of farming as a business. As such, this will lead to slow technology uptake and reduce opportunities for learning or training, resulting in restricted innovation and resilience in farmer-led irrigation.

The environmental and climatic Conditions were identified as the six groups of factors affecting the performance of FLID (Figure 3.16). This category identified 5 sub-factors: farmers experiencing declining crop yields due to climate change; drying boreholes and lower river flows; extreme temperatures (Increasing temperatures); irregular rainfall; and reduced water sources. All these factors expose FLID to climate risk.

3.4. Conclusion

This chapter provided a comprehensive characterization of farmer-led irrigation development in the Thulamela and Makhado municipalities of the Vhembe District and identified key determinants influencing farm performance. The findings of this chapter reveal that FLID is broader and more diverse in the Vhembe district than is often recognized but constrained by multiple factors. It is characterized by small farms operated by older farmers with tertiary and secondary (well-educated) education, who plant diverse crops. However, their potential is constrained by various factors, including a lack of institutional support, limited access to credit, high input and transportation costs, theft and vandalism, inadequate water licenses, inadequate infrastructure, limited extension support, and climate risk. These, together with high weed pressure, salinity problems, limited storage, and fencing, lack of water license, ultimately reduce long-term sustainability and efficiency. The advanced statistical analysis results demonstrate that soil and water-saving knowledge (PC1) and irrigation duration and scheduling (PC2) are the most significant drivers of farm income among FLID farmers. However, the negative association between irrigation training and income suggests that current training and institutional support mechanisms are poorly aligned with farmers' needs. Despite these constraints, these farmers become innovative and demonstrate resilience by managing their farms with limited external support and available resources. In addition, these findings collectively highlight that strengthening farmers' knowledge, upgrading irrigation management, improving access to appropriate technologies, and having access to extension and financial support are crucial to unlocking the economic and resilience potential of FLID in South Africa. Despite these contributions, the study has several limitations, including the sample size. Performance was measured primarily through income, while other factors that could be considered for future FLID performance include water-use efficiency and crop yields. Moreover, while PCA and MLR

regression capture performance through management, land condition, and farmers' perceptions and knowledge, further studies are needed to examine the institutions and markets, as well as these management practices over time. Future research can examine similar studies in other regions to compare results with this study.

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CHAPTER FOUR: FARMER-LED IRRIGATION PRACTICES AND WATER QUALITY EFFECT ON SELECTED SOIL PHYSICAL AND CHEMICAL PROPERTIES.

Abstract

In South Africa, FLID has become particularly important for smallholder farmers in Limpopo Province, where state-supported irrigation is limited. However, its effects on soil physicochemical properties remain insufficiently quantified in Vhembe District, South Africa. This study evaluated the effects of farmer-led irrigation practices and irrigation water quality on soil physical, chemical, and hydraulic properties in Thulamela and Makhado municipalities. Soil samples were collected from cultivated and fallow land at depths of 0–20 cm and 20–40 cm, and analyzed for physicochemical properties. Irrigation water was analyzed for EC, major cations, SAR, and nitrates. Data were evaluated using analysis of variance (ANOVA), correlation, and regression analyses. The results revealed that cultivated soils exhibited nutrient enrichment, with P at 17 mg/kg and $\text{NO}_3\text{-N}$ at 31 mg/kg, but no significant differences in physical parameters. Clay-rich Arcadia soils resisted compaction ($\text{BD } 1.05\text{--}1.25 \text{ g/cm}^3$), while sands showed vulnerability (BD up to 1.67 g/cm^3). Furthermore, borehole water showed elevated salinity ($\text{EC } 737 \mu\text{S/cm}$, $\text{SAR } 1.09$) versus river sources, driving regional sodicity, and was positively associated with increased soil exchangeable sodium and SAR, particularly in clay-rich Makhado soils. Similarly, Pearson correlation and regression analyses revealed significant relationships between irrigation water SAR and soil nitrate at 0–20 cm, suggesting that water quality influences nitrogen dynamics, while no significant structural degradation was detected. Soil water retention curves demonstrated enhanced surface water retention in cultivated soils, particularly in Thulamela. In conclusion, farmer-led irrigation practices enhanced surface nutrient status and hydraulic behavior, while irrigation water quality influenced sodicity risk. Continued monitoring and appropriate amendments are recommended to prevent long-term risks of sodicity and nutrient imbalances and to sustain productivity.

Keywords: Farmer-led irrigation Development (FLID), Soil physicochemical properties, irrigation water quality, soil water retention curve (SWRC), sodium adsorption ratio (SAR).

4.1. Introduction

Soil fertility, water resources, and irrigation infrastructure are key to crop production (Mavhungu et al., 2021, Materechera and Scholes, 2022, Kihara et al., 2023). This compels farmers to invest in costly external inputs and intensive management to sustain production (Gomiero, 2016). The ability of the soil to supply plants with essential nutrients is an essential component in food production, making soil fertility crucial for crop production (Mokgolo and Mzezewa, 2022, Smaling et al., 1997). According to the Department of Agriculture, Land Reform and Rural Development (2021) and Van Huyssteen and du Preez (2023) only a small fraction of South African's soils is considered highly suitable for agriculture, and most are inherently acidic, shallow, or nutrient-poor, making them highly susceptible to degradation under intensive use.

Many smallholder farmlands across South Africa, including those in the Vhembe district, occur informally on marginal lands previously designated as homelands, which are characterized by declining fertility (Mkuna and Wale, 2023, Magidi et al., 2021, Mokgolo and Mzezewa, 2022, Kihara et al., 2023, Bado and Bationo, 2018). Furthermore, these farmers are now experiencing poor field conditions due to extensive soil deterioration caused by erosion, nutrient depletion, poor water quality, and improper land management practices (Kihara et al., 2023, Bado and Bationo, 2018). These soils are characterized by acidic conditions, low nitrogen and organic carbon <1%, and phosphorus fixation, which together reduce resilience to climate change and limit crops' response to fertilizers (Mokgolo and Mzezewa, 2022, Preez et al., 2011).

In this context, emerging smallholder irrigation, particularly through farmer-led irrigation development (FLID), represents a vital pathway to food security and rural livelihoods in South Africa's semi-arid areas (Harmon et al., 2023, Van Koppen et al., 2017, Wiggins and Lankford, 2019). The FLID system has expanded rapidly, enabling farmers to grow a variety of crops in multiple cropping cycles annually on plots ranging from 1 to 5 hectares, despite the lack of government support, escalating climate variability, soil degradation, and water scarcity (Nesamvuni et al., 2022, Mkuna and Wale, 2023). Additionally, these farmers depend heavily on groundwater and rivers and use self-financed irrigation systems, including drip, furrow, and sprinkler methods.

Despite the benefits of FLID, its long-term sustainability is uncertain because it mostly depends on how different farmer-led irrigation practices interact with irrigation water quality and soil condition over time. Improper management practices and saline irrigation water often lead to soil

salinization, compaction, and nutrient imbalances, threatening long-term soil health sustainability and accelerating soil degradation (Sanga et al., 2024, Cuevas et al., 2019, Saffan et al., 2024b, Zaman et al., 2018). Elevated irrigation water can worsen soil conditions by replacing exchangeable $\text{Ca}^{2+}/\text{Mg}^{2+}$ with Na^+ , increasing salinity and compaction (bulk density $>1.4 \text{ g/cm}^3$), thereby reducing aggregate stability, available water capacity, and infiltration (Zaman et al., 2018, Cuevas et al., 2019, Mohanavelu et al., 2021, Saffan et al., 2024b, Mudaly and Van der Laan, 2020).

Furthermore, borehole water, common among FLID farmers, frequently exceeds FAO salinity thresholds ($\text{EC} >750 \text{ }\mu\text{S/cm}$, $\text{SAR} >3$), promoting sodicity on clay-rich soils, while river sources carry elevated nitrate and phosphate loads, accelerating nutrient leaching. Conventional tillage, common in many FLID systems, further disturbs soil structure, increases erosion, and can accelerate degradation, especially without proper monitoring, proper management practices that conserve moisture and protect the soil surface, and where inorganic fertilizer use is not complemented by organic amendments to increase organic matter (Munna and Lal, 2026).

Effective irrigation management under FLID, therefore, requires a nuanced understanding of both soil and water quality dynamics and how water influences soil physicochemical properties over time. However, farmers are unaware of the gradual changes in soil quality resulting from their repeated use of water sources and management practices, and there is limited empirical evidence linking FLID water quality to on-farm soil degradation in South Africa. This study aims to address these gaps by empirically quantifying how farmer-led irrigation practices and irrigation water quality affect selected soil physical and chemical properties on FLID farms in the Makhado and Thulamela municipalities of the Vhembe District, Limpopo Province. Additionally, this study explores linkages among water quality, soil properties, and management practices to infer the long-term sustainability of FLID systems in water-scarce areas and an environment prone to degradation.

4.2. Materials and Methods

4.2.1. Description of the study area

The study was conducted in the Vhembe District (22.7696° S , 29.9741° E), Limpopo Province, South Africa, situated in the far north of Limpopo Province and shares international borders with

Botswana and Zimbabwe to the northeast and Mozambique to the southeast, passing through parts of the Kruger National Park (Maponya, 2021). The region experiences a low and erratic annual rainfall between 246 – 700 mm, varying by subzones, and experiences high evapotranspiration in summer, and increasing intensity under climate change, resulting in high crop water demand and severe drought (Pieterse et al., 2024, Serote et al., 2023a). Agriculture is one of the major economic drivers in the region, and these conditions necessitate irrigation for smallholder production of vegetables, legumes, and cereals such as maize, primarily through farmer-led systems (drip, furrow, sprinkler) drawing from rivers and boreholes, and management practices to enhance production (Serote et al., 2023a, Materechera and Scholes, 2022, Mavhungu et al., 2021).

The sampling targeted the Makhado and Thulamela local municipalities which have varying soil types but are predominantly Hutton and duplex soils (such as Glenrosa), characterized by red-yellow apedal clay loams, black or brown soils, and red structured clays, according to the SA Soil Classification (1991). Samples were collected from eight farms, four in each municipality as shown in Figure 4.1.

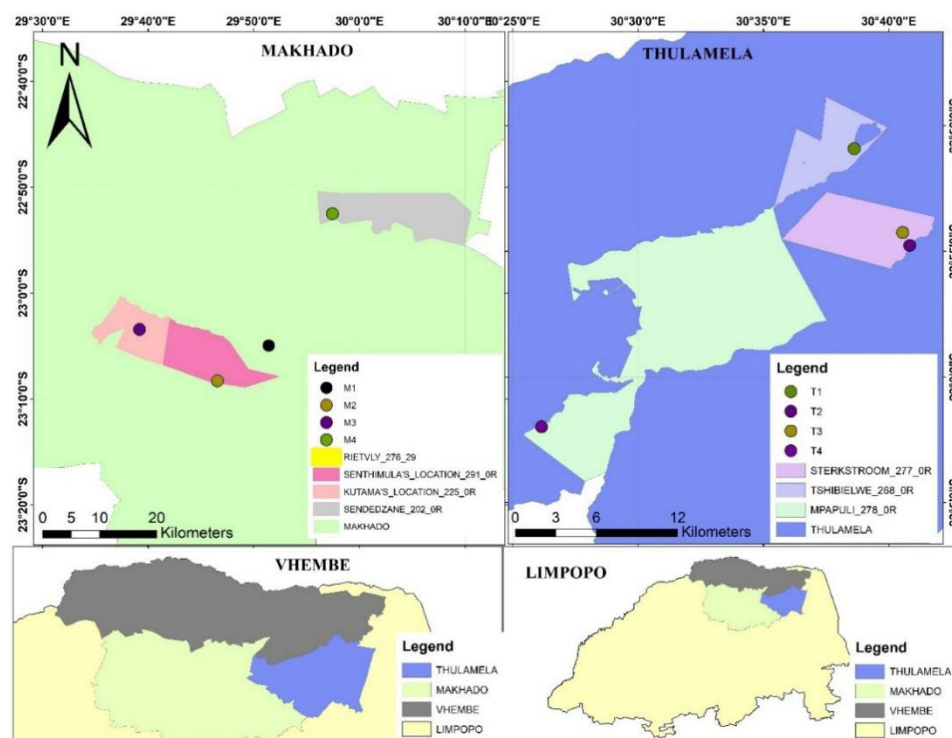


Figure 4.1: Study area map showing Vhembe District, Makhado and Thulamela municipalities, and eight sampled farmer-led irrigation farm locations (T1–T4 in Thulamela and M1–M4 in Makhado)

4.2.2. Land use and Farm selection

Preliminary data for this study were obtained from a structured questionnaire previously administered to 66 FLID farmers across Thulamela and Makhado municipalities (section 3). Due to resource constraints and based on the survey results, intensive soil and water sampling was focused on four farms in Makhado Municipality and four in Thulamela Municipality. Farms were selected to capture variability in diverse management practices, including tillage (conservation vs. conventional), irrigation systems (e.g., drip, sprinkler, furrow), and water sources (river vs. borehole), ensuring representation of FLID conditions in the district. On each selected farm, two fields were identified: the cultivated area under FLID management practices and a fallow area adjacent to it, serving as a reference. The eight FLID farms are characterized as depicted in Table 4.1 below, including water source, irrigation system, tillage practice, and cultivated area.

Table 4.1: Characteristics of eight farmer-led irrigation farms selected in Makhado and Thulamela local municipalities.

Farm Identity	Farm characteristics					Remarks
	Water source	Irrigation system	Tillage practices	Soil amendments	Cultivated Area (ha)	
T1	Borehole	Drip	Conservation	IF, PM, CM, MU	4	All farmer-led farms grow leafy vegetables and maize
T2	River	Drip and furrow	Conventional	IF, PM, CM	3	
T3	River	Drip	Conventional	IF, PM, CM	1.5	
T4	Borehole	Drip	Conventional	IF, PM, CM	3	
M1	Borehole	Drip	Conventional	IF, PM, CM	5	
M2	Borehole	Drip	Conventional	IF, PM, CM	4	
M3	Borehole	Drip and Sprinkler	Conventional	IF, CM	6	
M4	River	Drip and furrow	Conventional	IF, PM, CM	8	

M1 - M4 = Makhado, T1 - T2 =Thulamela, IF = Inorganic fertilizer, PM = Poultry manure, MU = Manure, CM = Cattle manure

4.2.3. Soil and Water sampling

Soil texture

Soil texture was determined using air-dried samples, sieved to <2 mm using the hydrometer method (Bouyoucos, 1962). 50 g of air-dried and sieved (<2 mm) soil was weighed into a beaker, saturated with distilled water, and then 10 ml of 3% Calgon solution was added, and the suspension was allowed to stand for 10 minutes. The suspension was transferred to a dispersing cup, mixed for 2 minutes using a high-speed stirrer, and then poured into a graduated cylinder. The cylinder was filled to 10000 mL with distilled water, and the plunger was inserted ten times. Hydrometer and temperature readings were taken immediately after 40 seconds and again after 2 hours of undisturbed settling. The percentages of sand, silt, and clay are calculated using Equations 4.1, 4.2, and 4.3, respectively.

$$\text{Silt (\%)} = 100 - (\% \text{clay} + \% \text{Sand}) \quad (4.1)$$

$$\text{Sand (\%)} = \left(\frac{\text{Sand weight (g)}}{\text{Soil mass (g)}} \right) \times 100 \quad (4.2)$$

$$\text{Clay (\%)} = \left(\frac{2 - \text{hour reading}}{\text{Soil mass}} \right) \times 100 \quad (4.3)$$

Where:

$$\text{Sand Weight} = \text{Soil mass} - (40\text{-second})$$

Bulk Density and Porosity Determination:

Bulk density (BD) was determined using the core ring method (Blake, 1965, Blake and Hartge, 1986). The core rings were oven-dried at 105°C until constant weight, and bulk density was calculated using Equation 4.4.

$$\text{Bulk density (BD)} = \frac{\text{Mass of dry soil (g)}}{\text{Volume of soil (cm}^3\text{)}} \quad (4.4)$$

Porosity was derived from the bulk density with a constant particle density of 2.65 g/cm³ using Equation 4.5.

$$\text{Porosity} = \left(1 - \frac{\text{Bulk density}}{\text{Particle density}}\right) \times 100\% \quad (4.5)$$

Aggregate Stability

A wet sieving method was used to determine soil aggregate stability (AS), which requires two sets of 8 cans (Nimmo and Perkins, 2002). 4.0 g of 2 mm air-dried soil was weighed into 8 sieves and pre-moistened for 5–10 minutes using wash bottles. The sieves were mounted in a wet-sieving apparatus, and the correctly labelled cans were placed beneath it and filled with distilled water. The sieves were then submerged in distilled water in the cans, and the machine was switched on and allowed to raise and lower the sieves for 3 minutes to separate unstable aggregates, with materials passing through collected in pre-weighed cans. The sieve holder was raised to allow the water to drain fully, then the cans were replaced with another set of 8 labelled cans containing an appropriate dispersing solution (2 g NaOH/L), and sieving continued for 5 to 8 min, until all remaining aggregates were fully dispersed. The sieve holder was raised, and all collected fractions were drained. Both sets of cans were oven-dried at 110 °C until the water evaporated, then weighed, with correction for the dispersant mass applied. Aggregate stability was calculated as the ratio of the mass of stable aggregates to the total soil mass using Equation 4.6.

$$\text{Aggregate stability (AS)} = \frac{\text{stable aggregates}}{\text{Stable aggregates} + \text{unstable aggregates}} \quad (4.6)$$

Where:

Stable aggregates = [(Weight of the dried can (NaOH) + content) - Weight of the can] – 0.2 g

Unstable aggregates = (Weight of the dried can (H₂O) + content) - Weight of the can

Soil Water Retention Curve:

The soil water retention curve (SWRC) was determined in the laboratory from undisturbed soil core rings using a sandbox apparatus at -100 cm matric potential (Hillel, 2003). Undisturbed soil cores from the field were carefully prepared, trimmed of excess soil, and covered on the bottom (sharp edge) with a piece of nylon cloth, which was secured with an elastic band. The sandbox was supplied and filled with a controlled water layer of 0.5 cm to cover the sand surface, and the core rings were placed in the sandbox with the bottom side down. The samples were saturated

gradually by capillary action from beneath to 1 cm below the ring top for over a period of a week before applying matric potentials (ψ) ranging from -0 to -100 cm using a sandbox (Eijkelkamp, Giesbeek, Netherlands). Saturated samples were weighed to determine water content at pF 0, then returned to the sandbox and subjected to a suction of -2.5 cm head to reach equilibrium. After equilibration, samples were reweighed and successively exposed to increasing suction levels using a suction regulator, ensuring equilibrium at each step. At each water potential, samples were weighed to determine soil water content, with soil-sand contact carefully restored throughout the procedure. The field capacity (FC) was taken at -100 cm matric potential, and the Pedotransfer Function was used to estimate soil moisture content at Permanent Wilting Point (PWP) (Saxton and Rawls (2006) based on soil texture and organic carbon content as illustrated in Equation 4.7.

$$\text{PWP} = 0.003(\% \text{Clay}) + 0.001(\% \text{Silt}) + 0.007 (\text{organic carbon (OC)}) \quad (4.7)$$

Thereafter, Available Water Content (AWC) was calculated using Equation 4.8.

$$\text{AWC} = \text{FC} - \text{PWP} \quad (4.8)$$

4.2.5. Soil Chemical Properties Analysis

The soil pH and electrical conductivity (EC) were determined with a pH meter and an EC meter, respectively, with a 1:2.5 soil: water ratio (Rhoades and Corwin, 1981). The Walkley-Black method was used to determine Organic Carbon (OC) (Walkley and Black, 1934) and Available Phosphorus (P) was extracted using the Bray 1 method (Bray and Kurtz, 1945). Exchangeable cations, including potassium (K^+) and sodium (Na^+), as well as cation exchange capacity (CEC), were extracted using 1 mol dm^{-3} ammonium acetate as described by Peech (1965). Inorganic nitrogen forms, namely ammonium-N ($\text{NH}_4\text{-N}$) and nitrate-N ($\text{NO}_3\text{-N}$), were extracted with 2 M KCl and analysed colorimetrically (Mulvaney, 1996). The sodium adsorption ratio (SAR) was calculated from measured exchangeable cations using Equation 4.9.

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{(\text{Ca}^{2+} + \text{Mg}^{2+})/2}} \quad (4.9)$$

4.2.6. Irrigation water quality analysis

The analysis included pH and electrical conductivity (EC), Total dissolved solids (TDS), major cations (Na^+ , Mg^{2+} , K^+ , and Ca^{2+}), major anions (Cl^- , SO_4^{2-} , HCO_3^- , NO_3^- , PO_4^{3-}), and selected micronutrients (e.g., B, Fe, Mn, Zn, Cu) in Appendix A. The measured ion concentrations, the sodium adsorption ratio (SAR) was calculated as described in Equation 4.9.

4.2.7. Statistical analysis

All data were subjected to analysis of variance (ANOVA) in Minitab version 19.0. Descriptive statistics (mean and standard deviation) were computed for all measured soil and water quality parameters. Water sources were grouped as per Table 4.1, with borehole vs. river sources compared using one-way ANOVA, and means were separated by Tukey's test. A two-way analysis of variance (ANOVA) was used to assess the effects of land use (cultivated vs fallow) and soil depth (0–20 cm and 20–40 cm), including their interaction, on soil physical, chemical, and hydraulic properties per farm. Where significant differences were detected ($p \leq 0.05$), mean separation was performed using the appropriate Tukey's test for mean comparisons. A three-way ANOVA (land use $\times$ depth $\times$ farm) assessed regional effects across Thulamela (T1-T4) and Makhado (M1-M4) farms, with farm as a random factor. Significant effects ($P \leq 0.05$) were followed by Tukey's test for mean separation.

Pearson correlation analysis was conducted to examine relationships between irrigation water quality parameters (EC, SAR, major cations, nitrates) and soil properties. Linear regression analysis was further applied to quantify significant relationships identified through correlation analysis, particularly between irrigation water SAR and soil nutrient indicators

4.3. Results and Discussion

4.3.1. Soil classification and texture distribution characteristics in the selected FLID farms

Table 4.2 presents the soil classification and texture characteristics of the eight FLID farms across Thulamela (T1-T4) and Makhado (M1-M4) municipalities in Vhembe District, Limpopo Province. Clay-textured soils prevail in T1 and M1, which are both classified as Arcadia form (Lonehill family) with both featuring Vertic A topsoils (10YR 2/1 Black and 10YR 3/1 Very Dark Gray, respectively)

overlying unspecified dark brown subsoils (10YR 2/2). These smectite-rich Vertisols display relatively high clay contents (25% and 56%, respectively), exhibit characteristic shrink-swell dynamics, self-mulching, crack formation, and strong structural development (Fey, 2010). Despite belonging to the same soil form, the difference in clay percentage between T1 and M1 indicates potential variation in physical and chemical behaviour under FLID practices and irrigation water quality (Table 4.2).

Table 4.2: Soil classification and texture characteristics of sampled FLID farms (n=8)

Farm identity	Topsoil Name	Colour (Topsoil)	Subsoil Name	Colour (Subsoil)	Soil Form	Soil Family	Particle size distribution			
							Clay (%)	Silt (%)	Sand (%)	Texture class
T1	Vertic A	10YR 2/1 Black	Unspecified	10YR 2/2 Very Dark brown	Arcadia	Lonehill	25	18	57	Sandy clay loam
T2	Orthic A	7,5YR 4/6 Strong Brown	Regic Sand	7,5YR 3/4 Dark Brown	Namib	Nortier	4	11	85	loamy sand
T3	Melanic A	7,5YR 3/3 Dark Brown	Lithocutanic B	7,5YR 2,5/2 Very Dark Brown	Mayo	Glenecho	35	25	40	Clay loam
T4	Humic A	5YR 2,5/2 Dark Reddish Brown	Red Apedal B	5YR 3/4 Dark Reddish Brown	Inanda	Himeville	22	11	67	Sandy clay loam
M1	Vertic A	10YR 3/1 Very Dark Gray	Unspecified	10YR 2/2 Very Dark brown	Arcadia	Lonehill	56	19	25	clay
M2	Orthic A	5YR 3/3 Dark Reddish Brown	Neocarbonates	5YR 4/3 Reddish brown	Augrabies	Hefnaar	13	10	77	Sandy loam
M3	Orthic A	2,5YR 4/5 Red	Red Apedal B	2,5YR 4/4 Reddish Brown	Garies	Nuwerus	5	13	82	loamy sand
M4	Orthic A	5YR 3/2 Dark Reddish Brown	Neocutanic B	5YR 3/3 Dark Reddish Brown	Oakleaf	Ritchie	14	8	78	Sandy loam

T1 – T4 = Thulamela, M1 – M4 = Makhado

In contrast, T2 (Namib form) and M3 (Garies form) are dominated by coarse-textured soils with very low clay contents (4–5%) and high sand fractions (>80%), corresponding to loamy sand textures (Table 4.2). Both T2 and M3 exhibit Orthic A topsoil (7.5YR 4/6 Strong Brown; 2.5YR 4/5 Red) over Regic Sand (7.5YR 3/4 Dark Brown) or Lithocutanic B (2.5YR 4/4 Reddish Brown) subsoil, respectively (Soil Classification Working Group, 1991). Course-textured soils include M2 Augrabies (Hefnaar) and M4 Oakleaf (Ritchie), which show Orthic A sandy loams (13-14% clay) over Neocarbonates (5YR 4/3 Reddish Brown) or Neocutanic B (5YR 3/3 Dark Reddish Brown) subsoils, reflecting moderate development under free drainage. Moderately textured soils include T3 Mayo (Glenecho), which shows Melanic A clay loam (35% clay, 7.5YR 3/3 dark brown) over Lithocutanic B, and T4 Inanda (Himeville) features Humic A sandy clay loam (22% clay, 5YR 2.5/2 dark reddish brown) over Red Apedal B, balancing infiltration with retention potential, suggesting stable aggregation and clay illuviation.

4.3.2. Soil physicochemical descriptive statistics

Physical properties

Table 4.3 presents the descriptive statistics of soil physical properties across the eight sampled FLID farms, revealing substantial variability in available water capacity (AWC), bulk density (BD), porosity, and aggregate stability (AS), consistent with the pedological diversity identified in Table 4.2. The overall means indicate moderate structural condition, with BD of 1.36 g cm^{-3} , porosity of 0.49, AWC of $0.24 \text{ m}^3 \text{ m}^{-3}$, and AS of 0.41. However, the high coefficients of variation (CV) of 17.23% for BD, 18.08% porosity, 43.47% for AWC, and 42.38% for AS indicate significant variability among FLID farms, particularly for water-related parameters and aggregate stability. This variability aligns with the pedological diversity described in Table 4.2, such as soil ranging from clay-rich M1 to sandy M3/T2, with over 80% sand (Soil Classification Working Group, 1991).

Table 4.3: Descriptive statistics of soil physical properties across sampled farms (mean $\pm$ SD).

Farm ID	Physical Properties			
	AWC	BD (g cm ⁻³)	Porosity	As
M1	0.29 $\pm$ 0.12	1.25 $\pm$ 0.19	0.53 $\pm$ 0.07	0.52 $\pm$ 0.24
M2	0.18 $\pm$ 0.10	1.52 $\pm$ 0.18	0.43 $\pm$ 0.07	0.48 $\pm$ 0.13
M3	0.17 $\pm$ 0.04	1.67 $\pm$ 0.19	0.37 $\pm$ 0.07	0.32 $\pm$ 0.07
M4	0.27 $\pm$ 0.05	1.41 $\pm$ 0.19	0.47 $\pm$ 0.07	0.54 $\pm$ 0.07
T1	0.31 $\pm$ 0.12	1.05 $\pm$ 0.11	0.60 $\pm$ 0.04	0.53 $\pm$ 0.12
T2	0.21 $\pm$ 0.15	1.32 $\pm$ 0.17	0.50 $\pm$ 0.06	0.16 $\pm$ 0.08
T3	0.29 $\pm$ 0.05	1.35 $\pm$ 0.10	0.49 $\pm$ 0.04	0.32 $\pm$ 0.08
T4	0.20 $\pm$ 0.04	1.29 $\pm$ 0.14	0.51 $\pm$ 0.05	0.38 $\pm$ 0.04
Overall Mean $\pm$ SD	0.24 $\pm$ 0.10	1.36 $\pm$ 0.23	0.49 $\pm$ 0.09	0.41 $\pm$ 0.17
Overall CV (%)	43.47	17.23	18.08	42.38

BD = Bulk density, AWC = Available water capacity, Porosity, AS = Aggregate stability, CV = Coefficient of Variation, SD = Standard deviation.

M1 and T1 (Arcadia soils with vertic properties) exhibit comparatively favourable structural characteristics with the lowest BD of 1.25 and 1.05 (g cm⁻³) and high porosity (0.53 – 0.60). Both farms also exhibited relatively high aggregate stability (0.52–0.53) and the highest AWC (0.29 to 0.31 m³ m⁻³). These properties are consistent with clay-rich smectitic soils containing shrink-swell properties, which promote aggregation and enhance water retention capacity (Fey, 2010). The lower bulk density and higher porosity reflect greater total pore space and greater structural development than in sandy soils. Although both T1 and M1 had the same soil, T1 exhibited superior performance, with the lowest BD and the highest AWC and porosity. This difference may reflect management influence, such as conservation tillage in T1, which enhances aggregate stability and maintains pore continuity relative to conventional tillage in M1. Nevertheless, both farms display stronger structural resilience than the coarse-textured soils.

In contrast, structurally vulnerable sands include M3, M2, and T2, where the highest BD was observed in M3 (Garies) and M2 (Augrabies), at 1.67 g cm⁻³ and 1.52 g cm⁻³, respectively, and poor AWC was 0.17 and 0.18 m³ m⁻³, respectively. These characteristics are typical of coarse-textured soils (previously classified in Table 4.2), which have limited aggregation and reduced

water-holding capacity. T2 exhibited very low aggregate stability (0.16), indicating structural vulnerability despite moderate BD (1.32 g cm^{-3}). Despite minor variation among these farms, the structural trend is consistent, such as limited aggregation, and the low AWC values ($0.17\text{--}0.21 \text{ m}^3 \text{ m}^{-3}$) indicating limited capacity to retain irrigation water. Such soils are generally more susceptible to compaction and structural degradation under intensive irrigation, particularly when saline water is applied or over irrigation and drying cycles. M4, T3, and T4 represent moderate structural conditions characterized by moderate BD, porosity, and AWC. M4 recorded AWC of $0.27 \text{ m}^3 \text{ m}^{-3}$, BD of 1.41 g cm^{-3} , porosity of 0.47, and notably the highest aggregate stability (0.54) among all farms. Despite its moderate bulk density, the high aggregate stability suggests strong inter-particle cohesion and structural resistance in M4. T3 and T4 display moderate density and porosity, reflecting balanced pore distribution typical of medium-textured soils. T3 showed BD of 1.35 g cm^{-3} , porosity of 0.49, and relatively high AWC ($0.29 \text{ m}^3 \text{ m}^{-3}$), whereas T4 exhibited BD of 1.29 g cm^{-3} , porosity of 0.51, and lower AWC ($0.20 \text{ m}^3 \text{ m}^{-3}$), likely reflecting its higher sand proportion. Additionally, aggregate stability values (0.32–0.38) suggest moderate structural resilience. These results reflect the balanced pore distribution typical of medium-textured soils, which often provide a balance between drainage and water retention, resulting in stable hydraulic performance.

Chemical properties

The descriptive statistics of soil chemical analyses from the sampled farms revealed significant variability in soil fertility and salinity indicators (Table 4.4). The overall mean soil pH was 5.74, ranging from 5.21 to 7.15, indicating slightly acidic conditions across the farms, with M4 showing the highest pH (7.15), falling within the optimal crop range. Most farms recorded pH values below 6.0, indicating potential aluminium toxicity in the most acidic soils, such as M2 (pH 5.36) and T3 (pH 5.21), which can limit nutrient availability, particularly phosphorus, calcium, and magnesium (Brady & Weil, 2016). Available P was critically deficient and highly variable across farms, averaging 10.6 mg kg^{-1} , and showing extreme variability (CV of 119%) driven by the T2 peak (24.6) versus the M1, M3, and T3 recording values below 5 mg kg^{-1} . This widespread P deficiency reduces maize and vegetable yields when fertilizers are not applied, particularly in highly weathered or Fe-rich soils where fixation processes dominate (Sparks et al., 2020). In contrast, exchangeable potassium was generally adequate ($143.00 \text{ mg kg}^{-1}$), although spatial heterogeneity was evident. Furthermore, electrical conductivity (EC) remained low across farms ($150.22 \text{ }\mu\text{S cm}^{-1}$).

Table 4.4: Descriptive statistics for soil chemical properties for sampled farms (mean $\pm$ SD).

Farm ID	Chemical properties									
	pH (KCl)	P (mg kg ⁻¹)	K (mg kg ⁻¹)	Na (mg kg ⁻¹)	CEC (cmol(+)/kg)	EC (μ S cm ⁻¹)	SAR	OC (%)	NH ₄ -N (mg kg ⁻¹)	NO ₃ -N (mg kg ⁻¹)
M1	5.66 $\pm$ 0.15	4.60 $\pm$ 2.72	172.25 $\pm$ 62.81	227.51 $\pm$ 35.39	25.32 $\pm$ 2.30	156.75 $\pm$ 68.81	7.26 $\pm$ 1.02	1.87 $\pm$ 0.71	112.03 $\pm$ 90.58	22.10 $\pm$ 16.32
M2	5.36 $\pm$ 0.63	7.36 $\pm$ 7.31	166.25 $\pm$ 29.45	63.45 $\pm$ 27.60	5.08 $\pm$ 0.67	122.00 $\pm$ 79.81	4.68 $\pm$ 1.89	1.90 $\pm$ 0.33	242.52 $\pm$ 249.53	6.66 $\pm$ 5.43
M3	5.30 $\pm$ 0.41	4.00 $\pm$ 1.91	132.50 $\pm$ 30.42	42.63 $\pm$ 23.63	4.15 $\pm$ 0.38	103.50 $\pm$ 54.73	3.44 $\pm$ 1.91	1.17 $\pm$ 0.38	199.47 $\pm$ 154.87	6.97 $\pm$ 2.57
M4	7.15 $\pm$ 0.18	12.63 $\pm$ 2.87	119.75 $\pm$ 7.06	33.76 $\pm$ 4.69	15.88 $\pm$ 3.26	163.25 $\pm$ 27.73	1.28 $\pm$ 0.05	1.10 $\pm$ 0.25	174.09 $\pm$ 167.35	16.67 $\pm$ 10.54
T1	5.77 $\pm$ 0.15	12.95 $\pm$ 13.80	127.50 $\pm$ 89.30	46.81 $\pm$ 4.40	18.58 $\pm$ 1.17	144.00 $\pm$ 51.22	1.69 $\pm$ 0.22	1.64 $\pm$ 0.64	126.93 $\pm$ 119.41	18.46 $\pm$ 17.71
T2	5.69 $\pm$ 0.36	24.56 $\pm$ 23.61	100.00 $\pm$ 68.49	32.12 $\pm$ 11.43	7.00 $\pm$ 1.44	180.00 $\pm$ 101.05	1.86 $\pm$ 0.56	1.28 $\pm$ 0.24	105.54 $\pm$ 99.34	22.82 $\pm$ 21.26
T3	5.21 $\pm$ 0.10	4.22 $\pm$ 2.21	123.25 $\pm$ 31.89	53.80 $\pm$ 9.47	18.05 $\pm$ 1.30	111.00 $\pm$ 36.77	1.96 $\pm$ 0.32	1.40 $\pm$ 0.31	147.55 $\pm$ 134.86	20.39 $\pm$ 8.87
T4	5.81 $\pm$ 0.76	14.52 $\pm$ 12.69	202.50 $\pm$ 72.12	34.45 $\pm$ 13.65	8.68 $\pm$ 2.46	221.25 $\pm$ 169.02	1.81 $\pm$ 0.47	1.78 $\pm$ 0.28	177.77 $\pm$ 169.25	34.34 $\pm$ 30.66
Overall Mean $\pm$ SD	5.74 $\pm$ 0.70	10.60 $\pm$ 12.59	143.00 $\pm$ 62.26	66.81 $\pm$ 64.66	12.84 $\pm$ 7.43	150.22 $\pm$ 89.57	3.00 $\pm$ 2.19	1.52 $\pm$ 0.51	160.74 $\pm$ 156.02	18.55 $\pm$ 18.04
Overall CV (%)	12.16	118.71	43.54	96.78	57.90	59.63	72.95	33.69	97.06	97.25

CV = Coefficient of Variation, SD = Standard deviation, P = Phosphorus (mg kg⁻¹), K = Exchangeable potassium, Na = Exchangeable sodium, SAR = Sodium adsorption ratio, OC = Organic carbon, NO₃-N = Nitrate nitrogen, EC = Electrical conductivity, NH₄-N = Ammonium nitrogen, CEC = Cation exchange capacity.

The exchangeable sodium and SAR showed substantial variability, with CVs of 96.78% and 72.95%, respectively. Notably, elevated levels of Na ($227.51 \text{ mg kg}^{-1}$) and SAR (7.26) were recorded for M1, indicating sodicity risk. Cation exchange capacity ranged widely from 4.15 to $25.32 \text{ cmol(+)}/\text{kg}$, with an overall mean of $12.84 \text{ cmol(+)}/\text{kg}$, suggesting variable nutrient retention capacity across farms. Organic carbon levels were low to moderate with an average of 1.52%, while mineral nitrogen ($\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$) exhibited a very high coefficient of variation of 97% CV.

4.3.3. Irrigation Water Quality Characteristics

4.3.3.1. Farm-level Irrigation Water Quality Assessment

Table 4.5 presents the irrigation water quality characteristics across eight FLID farms (Table 4.5), where borehole sources (6/8 farms) consistently show higher salinity and nutrient loading than rivers, posing differential risks to the texture-based soil groups identified earlier (clay M1/T1, coarse M2/M3/T2, moderate T3/T4/M4). The overall mean pH was 8.45, with a CV of 3.06%, ranging from 8.1 (T2 and M4, from river water) to 8.8 (M2 borehole water), indicating consistently alkaline conditions across the borehole and river sources. Although these values fall within acceptable irrigation limits (6.5–8.4), sustained use of alkaline water from farms such as M2 and M3, with pH exceeding 8.5, may gradually elevate soil pH and reduce the availability of phosphorus and micronutrients, particularly in initially acidic or weakly buffered sandy soils (Ayers & Westcot, 1985). Secondary and trace water quality parameters are presented in Appendix A.

Table 4.5: Key irrigation water quality indicators across the farmer-led irrigation farms (Mean $\pm$ SD)

Farm ID	Water source	Water parameters					
		pH	EC ($\mu\text{S/cm}$)	SAR	Na (mg/L)	Ca (mg/L)	NO ₃ -N (mg/L)
T1	Borehole	8.4 $\pm$ 0.1	410 $\pm$ 5	0.39 $\pm$ 0.01	12.05 $\pm$ 0.05	32.90 $\pm$ 0.10	74.26 $\pm$ 0.15
T2	River	8.1 $\pm$ 0.1	155 $\pm$ 5	0.53 $\pm$ 0.01	8.97 $\pm$ 0.06	10.75 $\pm$ 0.05	0.71 $\pm$ 0.01
T3	River	8.6 $\pm$ 0.1	630 $\pm$ 5	0.86 $\pm$ 0.01	30.85 $\pm$ 0.05	49.60 $\pm$ 0.10	5.96 $\pm$ 0.05
T4	Borehole	8.5 $\pm$ 0.1	595 $\pm$ 5	0.68 $\pm$ 0.01	24.20 $\pm$ 0.10	41.08 $\pm$ 0.10	58.41 $\pm$ 0.10
M1	Borehole	8.4 $\pm$ 0.1	609 $\pm$ 5	0.50 $\pm$ 0.01	18.46 $\pm$ 0.05	59.87 $\pm$ 0.11	0.14 $\pm$ 0.01
M2	Borehole	8.8 $\pm$ 0.1	1092 $\pm$ 5	2.26 $\pm$ 0.01	94.33 $\pm$ 0.06	32.65 $\pm$ 0.05	59.95 $\pm$ 0.05
M3	Borehole	8.7 $\pm$ 0.1	978 $\pm$ 5	1.61 $\pm$ 0.01	67.54 $\pm$ 0.05	39.99 $\pm$ 0.10	57.69 $\pm$ 0.10
M4	River	8.1 $\pm$ 0.1	174 $\pm$ 5	0.62 $\pm$ 0.01	11.24 $\pm$ 0.06	11.05 $\pm$ 0.05	2.43 $\pm$ 0.06
Overall Mean $\pm$ SD		8.45 $\pm$ 0.26	580.38 $\pm$ 322.75	0.93 $\pm$ 0.63	33.45 $\pm$ 29.64	34.74 $\pm$ 16.41	32.44 $\pm$ 31.21
Overall CV (%)		3.06	55.61	67.48	88.61	47.24	96.20

EC - Electrical Conductivity, TDS - Total dissolved solids, SAR - Sodium Adsorption Ratio, Na - Sodium, NO₃-N - Nitrate-N, Ca - Calcium, CV = Coefficient of Variation, SD = Standard deviation.

Similar observation was made on EC, with an average mean of 580 $\mu\text{S/cm}$ and moderate cv of 55.61% variability, where River water farms (T2 and M4) showed relatively low EC (155–174 $\mu\text{S cm}^{-1}$), whereas borehole farms, especially M2 (1092 $\mu\text{S cm}^{-1}$) and M3 (978 $\mu\text{S cm}^{-1}$), had higher EC approaching higher salinity hazard categories. This may lead to reduced crop growth and yield losses in sensitive crops under poor drainage conditions, especially on soil with low water content. Therefore, such levels may require careful leaching and drainage management to prevent salt accumulation and yield reductions.

Table 4.5 further shows that sodium concentrations were highly variable, with an average of 33.45 mg/L and a CV of 88.61%, and that borehole water had higher sodium concentrations than river water. However, SAR remained low across the farms, averaging 0.93 (0.39–2.26), indicating limited immediate sodicity risk. Nonetheless, prolonged sodium inputs can gradually impair soil structure in susceptible clay soils, even when SAR values are below critical thresholds (Pichu Rengasamy, 2010). Similarly, Nitrate-N exhibited extreme variability, with a CV of 96.20%, and several bioreholes (T1, M2, M3, and T4) exceeded 50 mg L⁻¹. Although nitrate-rich irrigation water

may supplement crop nitrogen requirements, excessive concentrations pose risks of leaching and groundwater contamination, particularly in coarse-textured soils (Phogat et al., 2021).

4.3.3.2. Irrigation water quality by source

The results of irrigation water quality parameters between borehole and river sources across FLID farms are presented in Table 4.6. Significant differences were observed in several parameters of irrigation water quality, with borehole water consistently showing higher salinity and nutrient concentrations than river water. This notable trend may pose risks to soil structural integrity, particularly on sodic clays (M1) identified earlier. The results revealed highly significant differences ($P < 0.01$) in irrigation water sources, with borehole water exhibiting a higher mean pH of 8.56 compared to 8.27 in river water. The slightly alkaline nature of borehole water could influence nutrient availability and soil pH over time, potentially increasing the risk of soil alkalinity if used consistently for irrigation (Ayers and Westcot, 1985). Calcium levels followed a similar pattern ($P < 0.01$), with borehole water containing 41.30 mg L^{-1} than river water 23.80 mg L^{-1} , suggesting that borehole water may contribute more to the cation balance and soil buffering capacity.

Table 4.6: Comparison of irrigation water quality parameters between borehole and river water sources

Parameter	Water Source		Significance
	Borehole (Mean $\pm$ SD)	River (Mean $\pm$ SD)	
pH	8.56 ± 0.19^a	8.27 ± 0.26^b	**
EC ($\mu\text{S/cm}$)	736.80 ± 265.00^a	319.70 ± 232.90^b	***
Sodium (mg L^{-1})	43.32 ± 33.22^a	17.02 ± 10.42^b	*
Calcium (mg L^{-1})	41.30 ± 10.27^a	23.80 ± 19.35^b	**
Nitrate-N (mg L^{-1})	50.09 ± 26.60^a	3.03 ± 2.32^b	***
SAR	1.09 ± 0.75^a	0.67 ± 0.15^a	ns

Means with different letters within rows indicate significant differences ($P \leq 0.05$). Significance levels are denoted as *** ($P \leq 0.001$), ** ($P \leq 0.01$), * ($P \leq 0.05$), and ns ($P \geq 0.05$).

Furthermore, statistical analysis showed a very highly significant ($P < 0.001$) difference between water sources, where borehole water exhibited significantly higher EC ($736.80 \mu\text{S cm}^{-1}$) and

nitrate-N (50.09 mg L^{-1}) relative to river water with EC ($319.70 \text{ }\mu\text{S/cm}$) and nitrate-N (3.03 mg L^{-1}). These results indicate that elevated EC and nitrate levels may contribute to salt accumulation and nitrate leaching if not properly managed, potentially affecting plant growth, crop nitrogen supply, and soil structure (Rhoades, 1984). Sodium concentration followed a similar pattern, showing a significant difference ($P \leq 0.05$) with borehole water containing 43.32 mg L^{-1} , significantly higher than river water 17.02 mg L^{-1} as depicted in Table 4.6. Despite higher sodium concentrations in borehole water, the Sodium Adsorption Ratio (SAR) values were low, and there were no significant differences ($P \geq 0.05$) between the borehole (1.09) and the river water (0.67), indicating a low overall sodicity risk for both sources. While borehole water is nutrient-rich, it has higher salinity and alkalinity levels than river water, and without proper management, such as soil testing, there is a risk of long-term soil degradation. Therefore, careful monitoring for sustainable irrigation management is advised.

4.3.4. Effect of region, land use, and soil depth on soil physicochemical properties

Region significantly influenced bulk density (BD), porosity, aggregate stability (AS), exchangeable sodium (Na), available phosphorus (P), and nitrate-N ($\text{NO}_3\text{-N}$) ($P \leq 0.05$), as depicted in Table 4.7. Soils from Makhado local municipality exhibited significantly higher BD (1.46 g cm^{-3}) and lower porosity ($0.45 \text{ m}^3 \text{ m}^{-3}$) than those from Thulamela (coarser textured dominant), with a BD of 1.25 g cm^{-3} and porosity of $0.53 \text{ m}^3 \text{ m}^{-3}$, indicating greater compaction. These differences are likely driven by the combined effects of higher clay content in certain farms (such as M1, with 56% clay content, identified in Table 4.2), reliance on borehole irrigation water with elevated sodium of 43 mg L^{-1} (Table 4.6), and intensive conventional tillage (Table 4.1). Increased BD under irrigated systems has been associated with repeated wetting-drying cycles and machinery compaction, especially in sandy soils with weak structure (Batey, 2009). Elevated sodium concentrations in irrigation water contribute to clay swelling, pore blockage, and aggregate dispersion, resulting in increased bulk density and reduced macroporosity over time (Rengasamy, 2010, Qadir et al., 2014)

Consistent with irrigation water quality patterns for borehole water (Table 4.5 and 4.6), exchangeable Na and SAR differed between regions, where Na and SAR were significantly higher in Makhado (91.8 mg kg^{-1} and 4.17) than in Thulamela (41.8 mg kg^{-1} and 1.83), confirming greater sodicity risk under continued groundwater irrigation (Rengasamy, 2010, Ayers and Westcot,

1985). Similar findings have been reported in semi-arid irrigated systems where long-term use of moderately saline groundwater increases soil Na accumulation and degrades physical structure (Qadir et al., 2014, Mohanavelu et al., 2021). Aggregate stability was significantly higher in Makhado (0.47) than in Thulamela (0.35), suggesting that although Makhado soils are highly compacted, their aggregates may be more cohesive, possibly due to higher clay content, which increases microaggregate formation

Table 4.7: Effects of region, land use, and soil depth on selected soil physical and chemical properties across FLID farms

Treatment	Physical Properties					Chemical Properties								
	BD	AWC	Porosity	AS	pH	P	K	Na	CEC	NH ₄ -N	NO ₃ -N	EC	SAR	OC
Region														
Makhado	1.46a	0.23	0.45a	0.47a	5.87	7.14a	147.70	91.8a	12.61	182.0	13.12a	136.4	4.17a	1.45
Thulamela	1.25b	0.25	0.53b	0.35b	5.61	14.06b	138.30	41.8b	13.08	139.5	24.02b	164.1	1.83b	1.56
Land use (LU)														
Cultivated (C)	1.41	0.25	0.47	0.36	5.97	17.04a	181.20a	77.8	13.84	173.8	31.29a	215.4a	3.60	1.36
Fallow (F)	1.30	0.23	0.51	0.45	5.51	4.16b	104.80b	55.8	11.84	147.7	5.85b	85.0b	2.39	1.65
Sampling depth (SD)														
0–20 cm	1.39	0.25	0.48	0.39	5.76	13.96	162.30a	63.7	12.91	230.3a	21.25	163.1	2.89	1.53
20–40 cm	1.33	0.23	0.50	0.42	5.72	7.24	123.80b	70.0	12.77	91.3b	15.89	137.3	3.10	1.48
P value														
Region	**	Ns	**	*	ns	*	ns	*	ns	ns	*	ns	**	ns
LU	ns	Ns	ns	ns	ns	***	***	ns	ns	ns	***	***	ns	ns
SD	ns	Ns	ns	ns	ns	ns	*	ns	ns	**	ns	ns	ns	ns
Region × LU	ns	Ns	ns	ns	ns	**	ns	ns	ns	ns	*	ns	ns	ns
Region × SD	ns	Ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
LU × SD	ns	Ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns
Region × LU × SD	ns	Ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

***, **, * = Significant at $P \leq 0.001$, $P \leq 0.01$, and $P \leq 0.05$, respectively; ns = not significant ($P \geq 0.05$), Means within columns followed by different letters differ significantly ($P \leq 0.05$), LU = Land use, C = Cultivated, F = Fallow, SD = Sampling depth, BD = Bulk density (g cm^{-3}), AWC = Available water capacity ($\text{m}^3 \text{m}^{-3}$), Porosity ($\text{m}^3 \text{m}^{-3}$), AS = Aggregate stability, pH = pH (KCl), P = Bray-1 phosphorus (mg kg^{-1}), K = Exchangeable potassium (mg kg^{-1}), Na = Exchangeable sodium (mg kg^{-1}), SAR = Sodium adsorption ratio, OC = Organic carbon (%), NO₃-N = Nitrate nitrogen (mg kg^{-1}), EC = Electrical conductivity ($\mu\text{S cm}^{-1}$), NH₄-N = Ammonium nitrogen (mg kg^{-1}), CEC = Cation exchange capacity (cmol (+)/kg^{-1}).

In contrast, Thulamela recorded significantly higher available phosphorus and nitrate-N (14.06 mg kg^{-1} and 24.02 mg kg^{-1} , respectively) than in Makhado (7.14 mg kg^{-1} and 13.12 mg kg^{-1}). This may be due to regional differences in fertilizer application intensity and manure incorporation, as most farms apply inorganic fertilizers (IF) combined with poultry or cattle manure (Table 4.1). Similar observation was made that sandy soils generally exhibit lower phosphorus fixation capacity and greater nitrate mobility, reduced aluminium content, contributing to higher measured mineral nutrient levels (Brady and Weil, 2002). Lastly, the results revealed no significant difference ($P \geq 0.05$) in pH, K, CEC, OC, EC, and $\text{NH}_4\text{-N}$ across regions, suggesting that intrinsic soil buffering capacity may moderate regional differences in water quality. The results align with a recent study by Mokgolo and Mzezewa (2022) reporting comparable low baseline phosphorus ($<8 \text{ mg kg}^{-1}$) across soils in Limpopo farms.

Effect of land use

The results revealed a highly significant difference ($P \leq 0.001$) between cultivated and fallow soil, indicating that land use exerted the strongest influence on soil chemical properties (Table 4.7). Cultivated soils contained significantly higher concentrations of available P (17.04 mg kg^{-1}), exchangeable K (181.2 mg kg^{-1}), $\text{NO}_3\text{-N}$ (31.29 mg kg^{-1}), and EC ($215.4 \mu\text{S cm}^{-1}$) compared to fallow soils with P (4.16 mg kg^{-1}), exchangeable K (104.8 mg kg^{-1}), $\text{NO}_3\text{-N}$ (5.85 mg kg^{-1}), and EC ($85.0 \mu\text{S cm}^{-1}$) showing signs of fertility gains. These highly significant differences, including elevated mineral N and P concentrations in cultivated soils, confirm substantial nutrient enrichment in FLID systems, particularly when inorganic fertilizers are combined with organic amendments (Matelele et al., 2024). Strong nitrogen enrichment is demonstrated by the more than 5-fold increase in $\text{NO}_3\text{-N}$, which is in line with repeated fertilizer inputs (Brady and Weil, 2017). There was no significant difference in soil SAR between. However, soil SAR increased by 51% from 2.39 in fallow (control) to 3.60 in cultivated area, indicating that borehole Na inputs (43 mg L^{-1}) and salinity buildup from borehole irrigation water, as shown in Table 4.6.

Despite pronounced chemical differences, land use did not significantly influence BD, AWC, porosity, or aggregate stability ($P \geq 0.05$). This suggests that soil chemical properties respond more rapidly to management intensity in nutrient accumulation than physical properties, which typically require longer-term structural disturbance or sustained sodicity to change significantly (Rengasamy, 2010, Qadir et al., 2014). Similarly, Table 4.7 reveals no statistically significant difference in organic carbon $\text{NH}_4\text{-N}$ between cultivated and fallow soils ($P \geq 0.05$). However, $\text{NH}_4\text{-N}$ levels were numerically higher in cultivated soils, possibly due to manure incorporation and

residue return in cultivated plots, which may offset mineralization losses under irrigation conditions. These findings highlight that management practices, particularly fertilizer and manure applications, are primary drivers of nutrient variability within the FLID systems, while physical properties remain largely unchanged.

Effect of soil depth

The majority of the physicochemical properties showed no significant differences with soil depth, indicating that sampling depth had comparatively limited effects. However, exchangeable K was significantly higher in the 0–20 cm layer (162.3 mg kg^{-1}) compared to the 20–40 cm layer (123.8 mg kg^{-1} ; $P \leq 0.05$). Similarly, $\text{NH}_4\text{-N}$ was significantly higher in the topsoil (230.3 mg kg^{-1}) than in the subsoil (91.3 mg kg^{-1}) ($P \leq 0.01$). These results indicate nutrient accumulation in the surface layer, likely due to fertilizer accumulation, manure incorporation, and limited downward mobility of ammonium in soil. Although there was no statistically significant difference in $\text{NO}_3\text{-N}$ across depth, $\text{NO}_3\text{-N}$ was numerically higher in the topsoil than in the subsoil. The absence of strong depth effects for most parameters suggests vertical redistribution of soluble nutrients under irrigation and mixing through cultivation within the 0–40 cm profile. Other properties, including bulk density, porosity, pH, P, and electrical conductivity, did not vary significantly with depth, suggesting that the soil profile is uniformly modified under current irrigation practices. The relative lack of vertical stratification aligns with drip and sprinkler irrigation systems that facilitate solute redistribution within the root zone, minimizing nutrient segregation compared to rainfed or conservation-tillage systems.

Interaction effect

Most interaction effects were not statistically significant, indicating that region, land use, and depth largely operated independently. However, a significant Region $\times$ Land Use interaction was observed for $\text{NO}_3\text{-N}$ ($P \leq 0.05$), and P ($P \leq 0.01$) suggesting that nitrogen accumulation, specifically $\text{NO}_3\text{-N}$, differed between Makhado and Thulamela under cultivation and fallow land. This interaction may be associated with differences in irrigation water nitrate concentrations from boreholes in Makhado, soil texture-mediated leaching dynamics, and the influence of clay-rich soils in moderating leaching, whereas sandy soils in Thulamela facilitated greater drainage and nitrate mobility. The absence of significant three-way interactions reinforces the idea that land-use effects dominate nitrogen and nutrient dynamics, with irrigation management exerting stronger control than combined pedological and regional effects.

4.3.5. Soil and water correlation between water and soil water retention curves (SWRC)

The soil water retention curves (SWRC) for Thulamela and Makhado municipalities revealed clear depth and land-use effects on soil hydraulic behaviour, reflected in saturation, field capacity (FC), permanent wilting point (PWP), and plant available water (PAW) as presented in Figure 4.8 and Figure 4.9. These parameters are likely driven by soil texture and management practices in farmer-led irrigation development (FLID) systems, where macropore-mesopore domains respond to amendments while micropores remain texture-controlled (Mzezewa, 2025, Myeni et al., 2021, Van Genuchten et al., 1992, Hohenbrink et al., 2023). Across both municipalities, water content declined progressively with increasing matric suction (where saturation falls are $0.43\text{--}0.54\text{ m}^3/\text{m}^3$ to PWP $0.084\text{--}0.094\text{ m}^3/\text{m}^3$), consistent with established soil physical principles and observations in subtropical smallholder farms (Van Genuchten et al., 1992, Myeni et al., 2021, Mzezewa, 2025).

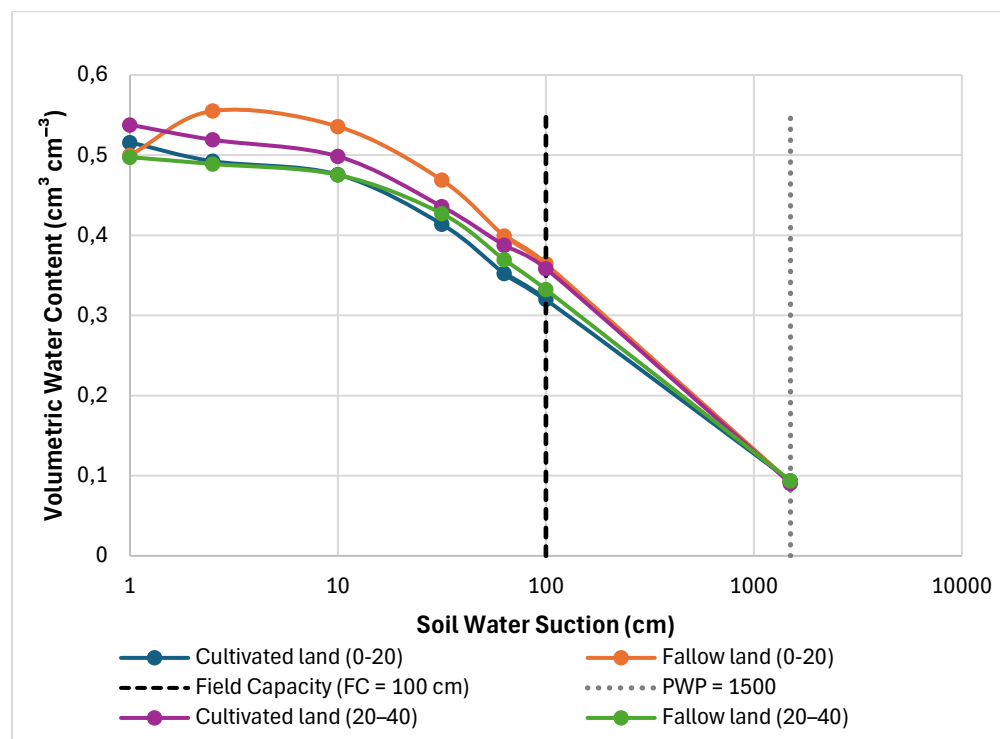


Figure 4.2: Average soil water retention curves for cultivated and fallow land uses at 0–20 cm and 20–40 cm depths in Thulamela Municipality

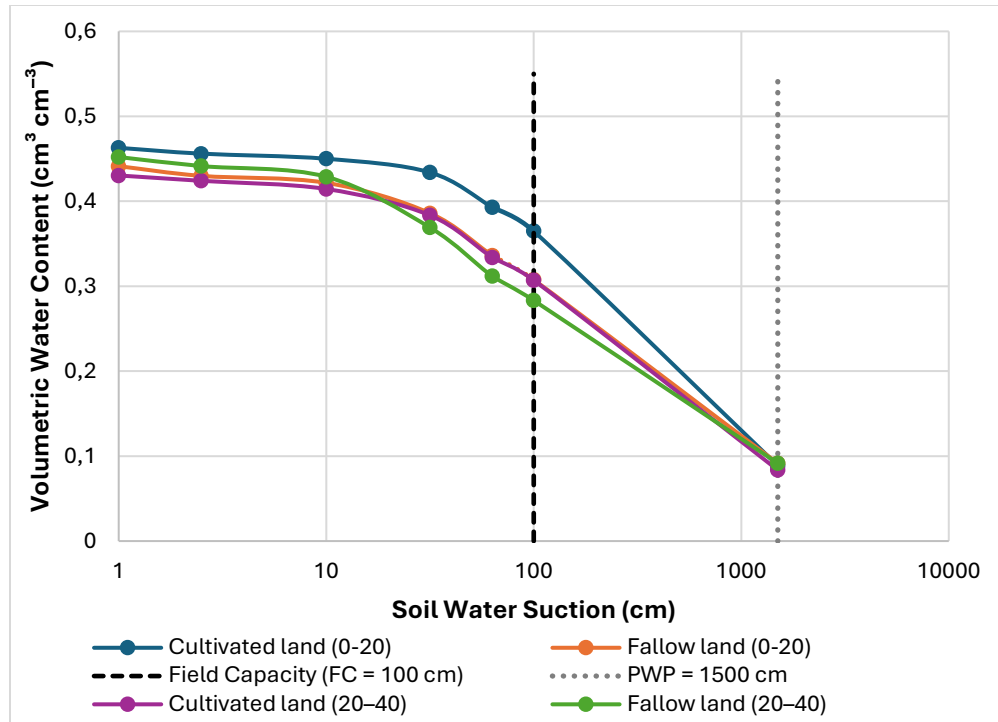


Figure 4.3: Average soil water retention curves for cultivated and fallow land uses at 0–20 cm and 20–40 cm depths in Makhado Municipality

In Thulamela, near-saturation water contents at 1 kPa ranged from 0.500 to 0.538 $\text{m}^3 \text{m}^{-3}$, with the highest value (0.538 $\text{m}^3 \text{m}^{-3}$) observed in cultivated soils at 20–40 cm depth, reflecting deep wetting from drip or furrow systems (Table 4.1). Furthermore, results suggest that farmer-led irrigation practices (organic and inorganic amendments, tillage practices, and irrigation systems) on the upper soil surface predominantly influenced macropores and mesopores, thereby improving surface hydraulic behaviour through enhanced aggregate formation. Similar improvements in surface hydraulic behaviour under managed systems have been reported where organic amendments increased structural stability and water-holding capacity (Rahman et al., 2017, Mokgolo et al., 2024). At intermediate suctions, fallow soils at 0–20 cm retained slightly more water than cultivated soils, indicating relatively greater mesopore storage in the undisturbed surface layer. At field capacity (100 kPa), fallow soils at 0–20 cm (0.364 $\text{m}^3 \text{m}^{-3}$) exceeded cultivated soils (0.320 $\text{m}^3 \text{m}^{-3}$), whereas at 20–40 cm, cultivated soils (0.358 $\text{m}^3 \text{m}^{-3}$) exceeded fallow soils (0.332 $\text{m}^3 \text{m}^{-3}$). Permanent wilting point values were similar across land uses and depths, ranging from 0.090 to 0.094 $\text{m}^3 \text{m}^{-3}$, which falls within the range for South African soils, indicating that tightly bound water was primarily governed by intrinsic soil texture rather than management (T3 clay loam soil with 35% clay) (Mzezewa, 2025, Myeni et al., 2021).

Consequently, plant available water (PAW) differed by depth, where in the surface layer, fallow soils exhibited greater PAW ($0.272 \text{ m}^3 \text{ m}^{-3}$) than cultivated soils ($0.226 \text{ m}^3 \text{ m}^{-3}$), while in the subsoil, cultivated soils had higher PAW ($0.268 \text{ m}^3 \text{ m}^{-3}$) than fallow soils ($0.239 \text{ m}^3 \text{ m}^{-3}$). This pattern suggests that in Thulamela, land-use effects were depth-dependent and influenced subsoil hydraulic properties more strongly than surface conditions.

In Makhado, cultivated soils consistently retained more water than fallow soils at 0–20 cm across all suction levels. At 1 kPa, cultivated soils contained $0.463 \text{ m}^3 \text{ m}^{-3}$ compared to $0.441 \text{ m}^3 \text{ m}^{-3}$ in fallow soils, and this trend persisted up to field capacity. FC was substantially higher under cultivation at both depths, reaching $0.365 \text{ m}^3 \text{ m}^{-3}$ in the surface layer compared to $0.308 \text{ m}^3 \text{ m}^{-3}$ under fallow. Subsurface cultivated soils also exceeded fallow soils at FC (0.307 vs $0.283 \text{ m}^3 \text{ m}^{-3}$). Permanent wilting point values remained relatively stable, ranging from 0.084 to $0.092 \text{ m}^3 \text{ m}^{-3}$. As a result, plant available water was consistently greater in cultivated soils, reaching $0.276 \text{ m}^3 \text{ m}^{-3}$ at 0–20 cm compared to $0.216 \text{ m}^3 \text{ m}^{-3}$ in fallow soils.

The stability of PWP across municipalities confirms that micropore-controlled water retention is largely determined by clay fraction and intrinsic texture, while differences in FC reflect modifications in mesopore distribution associated with land management (Myeni et al., 2021, Mzezewa, 2025, Saxton and Willey, 2005). This is supported by Gajić et al. (2023) with similar findings and who reported and linked the breakdown of structural aggregates by tillage tools to the creation of micropores in tilled soils, resulting from the destruction of macropores. Similar interpretations have been reported in classical soil hydraulic studies (Gajić et al., 2023, Myeni et al., 2021). The enhanced PAW observed in cultivated soils in Makhado indicates improved soil water storage capacity under farmer-led irrigation practices, whereas in Thulamela, the response was more variable and depth-specific. The study reveals that SWRC analysis shows that soil texture establishes the baseline hydraulic limits, while cultivation and irrigation practices modify field capacity and plant-available water without significantly altering the permanent wilting point. The absence of elevated PWP or abnormal curve shifts indicates that no structural degradation occurred under the observed management conditions. These findings confirm that farmer-led irrigation development influenced soil hydraulic functionality primarily through changes in mesoporosity and water storage dynamics rather than through alteration of intrinsic textural controls

In contrast, Makhado SWRCs showed a similar pattern, but with fewer differences between cultivated and fallow, with both depths nearly completely merged, with all lines tightly bundled

across suctions and minimal separation even at higher suctions. This indicates mineral composition and texture dominance, with sandy sites (M2/M3) anchoring the lower envelope and clayey M1 elevating the upper limit, both exerting stronger control over hydraulic behavior. While surface soils generally retained slightly more water than subsoils, depth-related differences were moderate compared to Thulamela. The reduced land-use effect in Makhado suggests that soil textural dominance limits structural modification under current irrigation practices.

4.3.6. Relationship between irrigation water quality and soil physicochemical properties

4.3.6.1 Surface Soil (0–20 cm)

Pearson correlation analysis (Tables 4.8 and 4.9) revealed significant relationships between irrigation water quality parameters and soil chemical properties at both 0–20 cm and 20–40 cm depths. At 0–20 cm soil depth, the region revealed significant interrelationships among irrigation water salinity and sodicity parameters (Table 4.8). A very strong positive correlation was observed between irrigation water EC (W_{EC}) and irrigation water Na (W_{Na}) of $r = 0.915$ ($P \leq 0.001$), and between W_{Na} and irrigation water SAR (W_{SAR}) of $r = 0.989$ ($P \leq 0.001$). Irrigation water SAR was also strongly correlated with W_{EC} ($r = 0.847$, $P \leq 0.01$). These results confirm that salinity (EC) and sodicity (SAR) hazards in the irrigation water are primarily driven by sodium concentrations. Similar relationships have been widely reported in irrigated systems where sodium is the dominant contributor to both EC and SAR values (Ayers and Westcot, 1985, Rengasamy, 2010). Additionally, Rengasamy (2010) Specifically, irrigation waters with elevated Na concentrations simultaneously increase both osmotic stress (via EC) and sodicity risk (via SAR), supporting the strong intercorrelations observed in this study.

At the soil level, exchangeable sodium (S_{Na}) showed a significantly positive correlation with soil SAR (S_{SAR}) ($r = 0.748^*$). In addition, S_{SAR} also showed a significant positive correlation with irrigation water EC ($r = 0.753^*$). These findings indicate that irrigation water salinity is already influencing sodicity development in the surface soil. Similar results were observed by Sheferia¹ and Seid (2021), who documented that repeated application of saline–sodic water promotes Na accumulation in the upper soil layer before redistribution to deeper horizons, and that these saline waters reduce organic carbon, organic matter, N, and K levels in the soil. Likewise Cucci et al. (2013) reported that an Increase in soil EC results from an increase in the concentration and salinity level of irrigation water.

Table 4.8: Pearson correlation coefficients (r) matrix between irrigation water quality and soil chemical properties at 0 – 20 cm depth

	W_EC	W_NO3	W_Na	W_SAR	S_Na	S_NH4	S_NO3	S_EC	S_SAR
W_EC	1.000								
W_NO3	0.529	1.000							
W_Na	0.915***	0.479	1.000						
W_SAR	0.847**	0.416	0.989***	1.000					
S_Na	0.292	-0.260	0.064	-0.018	1.000				
S_NH4	-0.326	-0.321	-0.306	-0.249	-0.342	1.000			
S_NO3	-0.614	-0.142	-0.749*	-0.773*	-0.028	0.215	1.000		
S_EC	-0.228	0.138	-0.235	-0.233	-0.153	0.260	0.745*	1.000	
S_SAR	0.753*	0.128	0.666	0.603	0.748*	-0.518	-0.468	-0.173	1.000

Significance levels: *** $P \leq 0.001$; ** $P \leq 0.01$; * $P \leq 0.05$, (W_EC = irrigation water electrical conductivity; W_NO₃-N = irrigation water nitrate–nitrogen; W_Na = irrigation water sodium; W_SAR = irrigation water sodium adsorption ratio; S_Na = soil exchangeable sodium; S_NH₄-N = soil ammonium–nitrogen; S_NO₃-N = soil nitrate–nitrogen; S_EC = soil electrical conductivity; S_SAR = soil sodium adsorption ratio)

Soil nitrate (S_{NO_3-N}) showed significant negative correlations with irrigation water Na ($r = -0.749^*$) and irrigation water SAR ($r = -0.773^*$). This suggests that increasing sodicity levels may reduce nitrate retention in the surface soil. Comparable observations were reported by Rietz and Haynes (2003), who found that elevated salinity and sodicity conditions can disrupt microbial processes, including nitrification, thereby influencing nitrate availability. Similarly, Hu and Schmidhalter (2005) noted that saline conditions may enhance nitrate mobility and reduce its retention in the root zone. A significant positive correlation was observed between soil nitrate (S_{NO_3-N}) and soil EC (S_{EC}) ($r = 0.745^*$), indicating that nitrate contributes substantially to soluble salt accumulation in the surface layer. Similar findings were reported by Diacono and Montemurro (2010), who demonstrated that nitrate accumulation under intensive fertilization significantly increases soil EC, particularly in irrigated vegetable production systems.

4.3.6.2 Subsurface Soil (20–40 cm)

At 20–40 cm depth (Table 4.9), the relationships between irrigation water quality and soil properties showed evidence of leaching processes. As observed in the surface soil, irrigation water parameters remained strongly intercorrelated ($W_{EC}-W_{Na}$, $r = 0.915^{***}$; $W_{Na}-W_{SAR}$, $r = 0.989^{***}$; $W_{EC}-W_{SAR}$, $r = 0.847^{**}$), confirming a consistent linkage between salinity and sodicity hazards in the irrigation water. This relationship further indicates progressive Na accumulation down the soil profile. However, fewer significant correlations were observed between irrigation water quality and subsurface soil properties compared to the topsoil (0 – 20 cm). Soil nitrate (S_{NO_3-N}) did not show significant correlations with irrigation water Na or SAR at this depth. Instead, a very strong positive correlation was observed between soil nitrate and soil EC ($r = 0.916^{***}$), which was notably stronger than in the surface soil. This stronger association of the $S_{NO_3-N}-S_{EC}$ relationship at this depth suggests that nitrate and soluble salts are closely linked and accumulated in the subsoil. Similar results were observed by Cameron et al. (2013) and Di and Cameron (2002), who reported that nitrate is highly mobile in irrigated soils and readily leaches below the topsoil, often accumulating in deeper layers. Exchangeable sodium (S_{Na}) remained significantly correlated with soil SAR ($r = 0.799^*$), confirming that sodicity processes are active and consistent in the subsurface soil. Comparable findings were reported by Qadir et al. (2007), who observed progressive downward movement of sodium under continuous irrigation, leading to redistribution of sodicity within the soil profile.

Table 4.9: Pearson correlation coefficients (r) matrix between irrigation water quality and soil chemical properties at 20–40 cm depth

	W_EC	W_NO3	W_Na	W_SAR	S_Na	S_NH4	S_NO3	S_EC	S_SAR
W_EC	1.000								
W_NO3	0.529	1.000							
W_Na	0.915***	0.479	1.000						
W_SAR	0.847**	0.416	0.989***	1.000					
S_Na	0.239	-0.309	0.029	-0.047	1.000				
S_NH4	0.234	0.284	0.250	0.206	0.381	1.000			
S_NO3	-0.449	-0.116	-0.608	-0.629	-0.046	-0.485	1.000		
S_EC	-0.194	0.102	-0.322	-0.347	0.019	-0.372	0.916***	1.000	
S_SAR	0.684	0.041	0.593	0.531	0.799*	0.562	-0.396	-0.163	1.000

Significance levels: *** $P \leq 0.001$; ** $P \leq 0.01$; * $P \leq 0.05$, (W_EC = irrigation water electrical conductivity; W_NO₃-N = irrigation water nitrate–nitrogen; W_Na = irrigation water sodium; W_SAR = irrigation water sodium adsorption ratio; S_Na = soil exchangeable sodium; S_NH₄-N = soil ammonium–nitrogen; S_NO₃-N = soil nitrate–nitrogen; S_EC = soil electrical conductivity; S_SAR = soil sodium adsorption ratio)

Comparison of the two depths provides strong evidence of vertical redistribution of nutrients and salts under irrigation. Firstly, the correlation between soil nitrate and soil EC increased from $r = 0.745^*$ at 0–20 cm to $r = 0.916^{***}$ at 20–40 cm. This strengthening of association indicates enhanced co-migration of nitrate and soluble salts downward through the soil profile. Similar vertical nitrate redistribution patterns have been reported in irrigated cropping systems by Cameron et al. (2013), who concluded that repeated irrigation promotes nitrate transport beyond the root zone. Secondly, significant negative correlations between irrigation water SAR and soil nitrate were observed in the surface soil but not in the subsurface soil. This suggests that nitrate affected by sodicity conditions at the surface is subsequently redistributed downward. Third, exchangeable sodium remained significantly correlated with soil SAR at both depths (0–20 cm: $r = 0.748^*$; 20–40 cm: $r = 0.799^*$), indicating continued sodium redistribution within the profile. Similar patterns of progressive sodicity development with depth under saline irrigation have been documented by (Rengasamy, 2010). The results from Tables 4.8 and 4.9 demonstrate that irrigation water quality directly influences surface soil sodicity, while nitrate and soluble salts are progressively redistributed to deeper layers through leaching. Such processes, if sustained over time, may increase risks of subsoil salinization and nutrient loss below the effective root zone.

4.4. Conclusion

This chapter comprehensively evaluated the physical and chemical soil properties, irrigation water quality, and their interactions within Farmer-Led Irrigation Development (FLID) systems in Vhembe District. The findings show that soil variability across farms is strongly influenced by inherent pedological differences, regional location, irrigation water source, and land use practices. Clay-rich soils (M1, T1) exhibited superior structural conditions, including low bulk density, high porosity, aggregate stability, and high available water capacity, while coarse-textured sandy soils (M2, M3, T2) showed high bulk density, low water retention, and structural vulnerability. Furthermore, this study reveals that FLID farms in Vhembe District enhance soil nutrient status under cultivation, with chemical properties showing substantial spatial variability between cultivated and fallow. Cultivated soils consistently had higher nutrient concentrations than fallow soils, with significant accumulation in available P, K, and mineral N, highlighting the positive impact of combined inorganic and organic fertilizer management under FLID practices. This is despite their reliance on moderately saline borehole water, which exceeds FAO thresholds in 75% of FLID farms. Topsoil (0–20 cm) accumulated more potassium and ammonium than subsurface layers, emphasizing topsoil nutrient enrichment under FLID practices.

Irrigation water quality differed significantly between sources and influenced soil properties, particularly sodicity (SAR) and salinity (EC). Borehole water exhibited higher EC, Na, and nitrate concentrations than river water, and these concentrations correlated positively with soil exchangeable sodium and SAR, especially in Makhado soils, signaling an emerging sodicity risk from Na accumulation. This could increase BD and reduce infiltration and available water content in the long term, especially under conventional tillage, as identified in Makhado. Soil water retention curves confirmed that land-use effects were more pronounced in Thulamela, where management enhanced surface hydraulic properties, whereas texture dominated in Makhado, limiting land-use influence. In conclusion, Farmer-led irrigation practices improve water retention in the topsoil, nutrient status (soil fertility), and agricultural productivity. They also introduce gradual risks associated with salinity, nutrient imbalance, and structural decline if not properly managed. As a result, sustaining soil health in FLID systems requires gypsum application on high-SAR sites, use of river water, conservation tillage (T1), texture-based irrigation scheduling, and routine soil and water monitoring to mitigate compaction and salinization on these low-OC (<1.5%) soils prone to erosion. The long-term viability of FLID systems in Vhembe District, therefore, depends on balancing productivity gains with informed, evidence-based soil and water management practices. Future research should investigate long-term changes using multivariate models, linking water ion composition with soil water retention curves (SWRC) and crop performance.

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CHAPTER FIVE: SUMMARY, CONCLUSION, AND RECOMMENDATIONS

This chapter presents the summary and conclusion based on the findings of the study, and further outlines the study's recommendations and gives suggestions for future research

5.1. Overall summary and discussion

The main objective of this study was to assess farmer-led irrigation development (FLID) and its associated agricultural water management practices in Vhembe District. The study integrated the socio-economic characterisation of farmers and irrigation systems with empirical soil and water quality analyses to evaluate performance and sustainability under semi-arid conditions. By linking farmer demographics, irrigation technology, groundwater quality, and soil properties, the study provides a comprehensive assessment of FLID. The findings from this study reveal that FLID in Vhembe District represents a structurally significant yet institutionally under-recognised pathway of agricultural intensification within South Africa. FLID operates largely outside state-led irrigation schemes and is characterised by private financing, groundwater dependence, and strong market orientation. Most farmers rely on borehole abstraction and drip irrigation systems, enabling multiple cropping cycles per year despite limited rainfall and the absence of direct government support. These findings confirm that FLID is not just for subsistence or temporary, but rather an established adaptive production system that contributes to rural income and the local food supply, responding to rainfall variability and unreliable surface water sources.

However, unlike large-scale commercial irrigation, FLID in Vhembe operates within tight financial margins, often supported by pension income and informal capital mobilisation. The socio-economic assessment revealed that income performance varies substantially across farms and is strongly influenced by irrigation capacity and integrated soil–water management knowledge. This indicates that technical farming skills play a crucial role in determining productivity outcomes than farm size. Similar observations have been reported in smallholder irrigation systems across semi-arid regions, where management intensity rather than scale drives profitability. The soil and water quality results introduce important sustainability considerations. Heavy reliance on groundwater revealed that borehole water samples exhibited moderate electrical conductivity and elevated sodium concentrations compared to river sources. While these levels do not yet indicate severe salinity or sodicity, statistical associations between irrigation water quality and soil sodium adsorption ratios suggest early-stage accumulation processes. Surface soils in borehole water source areas showed higher sodium concentrations and signs of structural sensitivity, particularly

in lighter-textured soils. At the same time, cultivated soils demonstrated significantly higher concentrations of available phosphorus, nitrate-nitrogen, and potassium compared to uncultivated reference areas, reflecting active fertilisation and manure application.

The hydrogeological influence of the Soutpansberg formation likely contributes to elevated mineral content in borehole water, increasing the probability of salt accumulation under insufficient leaching or drainage. In Vhembe, FLI farmers' perceptions of declining soil resilience correspond with these environmental indicators, suggesting that they already have knowledge that reflects emerging degradation processes. Soil texture emerged as a critical moderating factor. Clay-rich soils exhibited higher available water capacity and greater resilience to sodium accumulation, whereas sandy and loamy soils showed higher variability in hydraulic properties and greater vulnerability to nutrient leaching. This pedological differentiation highlights that FLID sustainability is not uniform across the district. Rather, it is mediated by site-specific soil characteristics interacting with irrigation water quality and management practices.

The management profile of FLID further reflects a combination of modern and traditional approaches. While drip irrigation adoption is relatively high, soil moisture monitoring remains limited, and conventional tillage dominates. As a result, water-saving infrastructure does not necessarily translate into optimised water productivity or effective salinity control. This imbalance suggests that irrigation modernisation has not been fully matched by soil diagnostic and conservation practices. Institutionally, FLID operates with limited integration into formal water governance structures. Limited awareness of Water User Associations and weak participation in licensing or regulatory frameworks suggest that groundwater abstraction occurs largely outside coordinated oversight. In the absence of systematic monitoring, cumulative abstraction and salinity risks remain unquantified. These governance gaps increase environmental uncertainty and highlight the need for active institutional alignment with farmer-led irrigation expansion.

5.2. Conclusion

This study confirms that farmer-led irrigation development in Vhembe District plays a meaningful role in sustaining smallholder agricultural production under semi-arid climatic conditions. Farmers independently search for resources, invest in irrigation infrastructure, self-finance, and adopt water-efficient technologies that support multiple cropping cycles and income diversification, despite marginal soils. The evidence shows that income performance is strongly influenced by integrated soil and water management knowledge, showing the importance of technical skills in

smallholder irrigated farms. However, sustainability in these FLI farms remains conditional. Moderate to high salinity risks associated with groundwater dependence, combined with soil texture variability and limited soil moisture monitoring, create differentiated vulnerability across farms. Although no severe degradation was observed, early indicators of sodium accumulation suggest that continued reliance on groundwater without monitoring could gradually constrain long-term productivity if not managed properly. This risk is likely to continue increasing due to a lack of institutional support for these farmers, who operate outside government and receive no help with groundwater management or technical advice from extension workers, which further increases risks. As a result, FLID should be recognised as a crucial irrigation pathway that requires active environmental governance and policy integration by the government in place to guarantee its sustainability, rather than addressing degradation after it has already occurred.

5.3. Recommendation

To strengthen the sustainability and performance of farmer-led irrigation development, the study recommends the following interventions:

- 5.3.1. Farmer-led irrigation development should be formally incorporated into national and provincial irrigation planning frameworks by registering, receiving recognition in water allocation strategies, and inclusion in agricultural support programmes to ensure that independent irrigators are integrated and recognised within formal water governance systems and supported by established policy programmes.
- 5.3.2. A structured groundwater monitoring programme should be established to routinely assess borehole water quality, salinity trends, and abstraction levels in regions such as the Vhembe District, enabling early detection of salinity accumulation and preventing long-term soil salinity and degradation in groundwater-dependent farming areas, and ensuring sustainable resource use.
- 5.3.3. Extension services should prioritise integrated soil and water management training, including irrigation scheduling, soil moisture monitoring technologies, gypsum application where appropriate, conservation tillage practices, and balanced nutrient management, to enhance water productivity and protect long-term soil resilience. Furthermore, farmer organisations and Water User Associations should be supported to improve collective action, regulatory compliance, and market access.

- 5.3.4. Financial support, such as funding and targeted subsidies for water storage systems and energy-efficient pumping technologies, should be developed to reduce operational cost challenges for farmers and boost farm profitability and economic resilience.

5.4. Future research

- 5.4.1. Long-term longitudinal monitoring studies are needed to quantify soil salinity trajectories and changes in groundwater quality under sustained farmer-led irrigation, particularly in areas dependent on boreholes in the Vhembe District.
- 5.4.2. Further studies should develop an integrated soil–water–economic model to simulate how irrigation scheduling, soil hydraulic properties, and groundwater quality interact to influence farm profitability and sustainability in order to identify optimal management strategies that maximise income while minimising soil degradation risks in groundwater-dependent systems under semi-arid conditions in South Africa.
- 5.4.3. Future research should focus on comparative research across different provinces and agroecological zones in South Africa to determine whether the structural characteristics, groundwater dependence patterns, and sustainability risks observed in Vhembe represent localised conditions or broader national trends in farmer-led irrigation expansion.

CHAPTER SIX: REFERENCES

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APPENDICES

Appendix A: Secondary and Trace Irrigation Water Quality Parameters (Mean $\pm$ Standard Deviation) for the Eight Study Farms

Farm ID	Water source	Water parameters									
		TDS (mg/L)	Total Alkalinity (mg/L)	SO ₄ (mg/L)	Cl (mg/L)	NH ₃ -N (mg/L)	Mg (mg/L)	Fe (mg/L)	Mn (mg/L)	Zn (mg/L)	B (mg/L)
T1	Borehole	282.6 $\pm$ 2.5	96.63 $\pm$ 1.52	6.21 $\pm$ 0.10	18.45 $\pm$ 0.15	0.324 $\pm$ 0.005	23.19 $\pm$ 0.10	0.076 $\pm$ 0.005	0.0044 $\pm$ 0.0005	0.074 $\pm$ 0.005	0.02 $\pm$ 0.01
T2	River	107.0 $\pm$ 2.0	56.10 $\pm$ 1.01	2.16 $\pm$ 0.15	8.50 $\pm$ 0.10	0.275 $\pm$ 0.005	6.93 $\pm$ 0.06	0.254 $\pm$ 0.005	0.059 $\pm$ 0.001	0.054 $\pm$ 0.005	0.02 $\pm$ 0.01
T3	River	435 $\pm$ 3	242.63 $\pm$ 2.51	7.81 $\pm$ 0.10	36.15 $\pm$ 0.15	0.656 $\pm$ 0.005	28.79 $\pm$ 0.10	0.856 $\pm$ 0.005	1.935 $\pm$ 0.056	0.104 $\pm$ 0.005	0.06 $\pm$ 0.01
T4	Borehole	411 $\pm$ 3	183.07 $\pm$ 2.00	18.11 $\pm$ 0.10	29.76 $\pm$ 0.15	0.244 $\pm$ 0.005	33.24 $\pm$ 0.06	0.165 $\pm$ 0.005	0.0026 $\pm$ 0.0005	0.085 $\pm$ 0.005	0.02 $\pm$ 0.01
M1	Borehole	420 $\pm$ 3	152.13 $\pm$ 2.01	9.75 $\pm$ 0.15	30.46 $\pm$ 0.15	0.255 $\pm$ 0.005	27.43 $\pm$ 0.06	0.155 $\pm$ 0.005	0.012 $\pm$ 0.0006	0.094 $\pm$ 0.005	0.06 $\pm$ 0.01
M2	Borehole	753 $\pm$ 3	414.07 $\pm$ 2.00	34.09 $\pm$ 0.10	70.20 $\pm$ 0.10	0.285 $\pm$ 0.005	60.05 $\pm$ 0.05	0.086 $\pm$ 0.006	0.0024 $\pm$ 0.0005	0.064 $\pm$ 0.005	0.28 $\pm$ 0.01
M3	Borehole	674 $\pm$ 3	269 $\pm$ 2	33.89 $\pm$ 0.10	58.15 $\pm$ 0.15	0.206 $\pm$ 0.005	56.94 $\pm$ 0.05	0.056 $\pm$ 0.005	0.0026 $\pm$ 0.0005	0.074 $\pm$ 0.005	0.29 $\pm$ 0.01
M4	River	120 $\pm$ 3	50.60 $\pm$ 1.51	4.10 $\pm$ 0.10	12.75 $\pm$ 0.15	0.305 $\pm$ 0.005	8.10 $\pm$ 0.10	0.804 $\pm$ 0.005	0.054 $\pm$ 0.005	0.026 $\pm$ 0.005	0.03 $\pm$ 0.01

Appendix B: Informed Consent Form

INFORMED CONSENT FORM

Brief Introduction: My name is Natalian Madikelele Mamogobo. I am a student researcher enrolled in the Master of Science in Agriculture (Specialization: Soil Science) at the University of Venda.

The purpose of the study is: To assess the Farmer-led Irrigation Development (FLID) in South Africa: A case study of Vhembe District.

Procedures: This survey is voluntary and will take approximately 30 minutes to complete. In this research, you will be asked to answer questions about Farmer-led irrigation development. Withdrawal from participating in the study is accepted without any threats, and you may pass on any question that makes you feel uncomfortable. However, to make data collection and representation easier, there is an emphasis on high participation. I will ensure that any information you share during the interview remains private.

Compensation: There will be no compensation for participating in this research.

Feedback and dissemination plan: Data will be disseminated through gatherings, traditional council meetings, and presentation of the findings and recommendations to relevant stakeholders and the community at large. The study will also be published and presented at conferences.

INFORMED CONSENT: I hereby confirm that I have been adequately informed by the researcher about nature, and I have also received, read, and understood the above-written information. I am aware that the study's results will be anonymized and included in a research report. I understand that my participation is voluntary and that I may, at any stage, without prejudice, withdraw my consent and participation in the study. I had sufficient opportunity to ask questions and, of my own free will, declared myself prepared to participate in the study.

Research participant's name:.....Signature:..... Date:.....

Researcher's name:.....Signature:..... Date:.....

Appendix C: Questionnaire

QUESTIONNAIRE



The purpose of this questionnaire is to “evaluate pathways to sustainable agricultural water management: Case studies of smallholder communities in rural and peri-urban areas of the Limpopo and Gauteng Provinces”. The information of each participant will be kept private. Please make sure you only answer questions associated with the pathway you are currently farming under. Use an "X" next to the code to answer the questions where appropriate. Should you feel uncomfortable answering any question, please leave the item blank and answer the next question.

INTERVIEWER DECLARATION:

I, ...

Declare that I will ask this questionnaire as it will be laid out. I declare that all responses recorded will be the true responses of the respondent and that I have thoroughly checked the questionnaire.

Signature :

Date :

District :

Municipality :

SECTION A: DEMOGRAPHICS CHARACTERISTICS

A1	A2	A3	A4	A5	A6	A7
How old are you?	Gender? 1 = Male 2 = Female	Marital status 1 = Married 2 = Single 3 = Divorced 4 = Widow/widower	Do you have a disability 1 = Yes 2 = No	Number of people in the household	What is your highest level of education? 1 = No formal education 2 = Primary Education	What is the total monthly income of your household from all sources? R.....

		5 = (Other, specify)			3 = Secondary education 4 = Tertiary education	
A8	A9	A10	A11			
What are the main ways your household earns money? (You can select more than one) 1=Salaries from jobs R..... 2=Small business 3=Pension 4=Government grants 5=Money sent by family members (remittances) 6=Other(specify)	Who is the household head? 1= Father 2= Mother 3=Sister 4=Brother 5=Grandparents	Race 1= black 2= colored 3= white 4=.....	What type of soil do you have on your farm? 1= Sandy soil? 2= Loamy soil? 3= Clay soil? 4= Not sure?			

SECTION B: FARMING CHARACTERISTICS

B1	B2	B3	B4	B5	B6	B7
Are you a full-time farmer? 1 = Yes 2 = No	How many years have you been farming? (years)	Total farm size (ha) Ha Land Underutilization How do you feel about your land size?	Type of land ownership: 1=Own land 2=Rent 3=Permission to occupy (PTO) 4 =State owned 5=Communal land 6= Other (specify)	What is the main crop that you plant on your farm? What other crops do you also plant on your farm? 	Do you produce any indigenous crops? (e.g., cowpea, bambara groundnuts, okra, amaranthus) 1=Yes 2=No If yes, please list the indigenous	What type of labour do you use? 1 = Hired 2 = Family 3 = Both Total number of labourers: Males:

		1=Too small 2= Just right 3=Too large Would you want to expand? 1 = Yes 2 = No	Are you satisfied with the security? 1 = Yes 2 = No		crops that you produce. 	Females:
B8	B9	B10	B11	B12	B13	
Main reasons for engaging in farming (You can select more than one) 1=Income generation 2=Food security 3=Home consumption 4=Other (specify)	Do you see your farming as a business? 1=Yes 2= No	What was your total farm income over the past year? R.....	What are the sources of income that have contributed to your total farm income over the past year? (You can select more than one) 1=Crop sales (income from selling grains, vegetables, etc.) 2= Livestock sales (income from selling cattle, poultry, goats, etc.) 3=By-products (e.g., selling manure, hay bales, or seeds) 4= Farm-related services (e.g., ploughing, harvesting for others) 5= Agri-tourism (e.g., income from farm visits or tours) 6= Other farm-related income (please specify):	Do you have enough food all year round? 1=Yes 2=No	How do you classify yourself? 1=Extremely poor 2=Poor 3=Lower middle class 4=Upper middle class 5=Rich	

SECTION C: Land conditions and farming practices

C1. How would you rate the condition of your land for growing crops? **(Please select all that apply)**

Land Condition	Good	Fair	Poor
Drainage (Water does not stay on the surface)			
Water holding capacity (Soil keeps water well)			
Low weed pressure (Few weeds grow on the land)			
Nutrient supply (Soil has enough nutrients for crops)			
Salinity problems (Soil is salty and affects crops)			
Resilience to degradation (Land stays good even in tough conditions)			

C2. Which farming practices are you using on your farm? **(Please select all that apply)**

Farming practices		Tick
Tillage practices (How do you prepare the soil before planting?)	Minimum/zero tillage (Barely turning the soil, or not at all)	
	Conventional tillage (Ploughing or turning the soil as usual)	
	Conservation tillage (Turning the soil a little to keep it healthy)	
	Other (specify):	
Cropping systems (How do you plant your crops?)	Inter-cropping (Planting different crops together on the same land)	
	Mono-cropping (Planting the same crop on the same land)	
	Crop rotation (Changing crops on the same land from season to season)	
	Other (specify):	
Soil management practices (How do you take care of the soil?)	Organic fertilizers (Using natural materials like manure or compost)	
	Inorganic fertilizers (Using chemical fertilizers like NPK)	
	Cover crops (using grass or beans to protect the soil, keep it healthy, reduce weeds, and hold water in the soil)	
	Other (specify):	

C3. Why did you choose the farming practices mentioned in C2?.....

.....

.....

.....

SECTION D: FARM ASSETS

D1. Indicate the assets that you have access on your farm.

Category	Assets	Number of items owned	Ownership: Government/ Household head (HHH)
Water management Equipment	Water Pump (Electric/Diesel)		
	Irrigation System Components (e.g., drip lines, sprinklers)		
	Water Storage Tanks		
	Borehole		
	Reservoir		
	Other(specify):		
Soil Preparation	Animal-drawn Plough (plough pulled by cows or donkeys)		
	Tractor-drawn Plough (plough pulled by a tractor)		
	Tractor		
	Hand Tools (e.g., hoes, spades, rakes)		
	Other (specify):		
Transportation and Handling	Wheelbarrow		
	Trailer		
	Vehicle (e.g., truck, pickup)		
	Other (specify):		
Post-Harvest Equipment	Packhouse/Storage		
Other Farm Assets	Fencing		
	Greenhouses/Polytunnels		
	Other (specify):		

SECTION E: Institutional and infrastructure information

E1	E2	E3	E4	E5	E6
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Membership in farmer organisations 1=Yes 2=No If yes, what is/are these organization(s) 	Do you have access to extension services? 1=Yes 2=No If yes, where do they come from? 1=Government agricultural department 2=NGO 3=Agricultural cooperative 4=Local community-based organization 5=Private sector	If yes, what kind of services do they offer? (You can select more than one option) 1=Production 2=Marketing 3=Training 4=information provision 5=Other (specify) Frequency of visits per month 	Have you received any credit support in the past 3 years? And from who? 1= Yes 2= No Sources of credit support: (You can select more than one option) 1=Formal financial institution 2=Relatives 3=Money lenders 4=Other (specify) If No, what are the reasons?	Do you have any access to market? 1=Yes 2=No Type of market used How much percentage of the output do you sell? %	Distance between your farm and the market. km Distance between the place where you buy your farming supplies and your farm. km Transport used 1=Own 2=Hired 3=Both
E7		E8		E9	
What is the condition of the road from your farm to the market? 1= Tarred Road		What challenges do you face when marketing your produce?		What do you think can be done to address these challenges?	

2= Tarred with potholes 3=Gravel Road Rate the quality of the road: (1=very poor; 2=poor, 3=good, 4=excellent)		
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SECTION F: WATER ACCESS AND AVAILABILITY

Important Note: Rain-fed farmers who do not use any additional water sources should skip Sections F, G and H.

F1. How many times per week do you have access to water on your farm?

.....

F2. Is water available throughout the year?

Yes	No
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SECTION G: WATER COSTS

G1. Are you currently paying for the water you use on your farm? (If no, skip to question G4)

Yes	No
-----	----

G2. If yes, how do you pay for water?

Same amount every month	Based on the amount of water used (metered)
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G3. How much do you pay monthly for water?

R.....

G4. Would you be willing to pay for the water if you weren't already paying?

Yes	No
-----	----

G5. If yes, how much are you willing to pay monthly? R.....

G6. If no, what would be the reason you are not willing to pay? **(Please select all that apply)**

Reason for Not Willing to Pay	Tick
Too expensive	
Water should be free	
Not enough water available to justify the cost	
Other (please specify)	

G7. How much do you pay for water expenses (electricity/diesel/petrol)?

R.....

SECTION H: WATER USE EFFICIENCY (How Well You Use Water on Your Farm)

H1. How do you determine when and how much water to apply to your crops? **(Please select all that apply)**

Methods used to determine and monitor water application on your crops	Tick
Crop growth stages (Adjusting water based on specific developmental stages of the crop)	
Visual checks (Using sight to assess soil moisture and plant health)	
Instrument measurements (Using tools like soil moisture sensors, water meters)	
Schedule & expert visits (Following a planned irrigation schedule and receiving guidance from experts)	
Trainings & peer learning (Learning through workshops and advice from other farmers)	
Other (please specify)	

H2. How long do you typically irrigate your crops? hr/mins

SECTION I: PERCEPTION ON WATER SAVING METHODS (Your Views on Water-Saving Methods)

I1. How much knowledge do you have about the following water-saving methods? (Use the following scale: 1 = No knowledge, 2 = A little knowledge, 3 = Some knowledge, 4 = A lot of knowledge)

Water-saving methods	1	2	3	4
Drip irrigation (watering plants slowly through small pipes)				
Soil moisture monitoring (checking how wet or dry the soil is)				

Mulching (covering soil with leaves or grass to keep it wet)				
Efficient irrigation scheduling (planning when and how much to water)				
Use of drought-resistant crop varieties (growing crops that need less water)				

12. How important do you think using methods to save water is for the future of your farm? (Use the following scale: 1 = Not important, 2 = A little important, 3 = Important, 4 = Very important)

Scale	Tick
Not important	
A little important	
Important	
Very important	

13. How big of a problem do you think each of the following is when trying to use water-saving methods on your farm? (Use the following scale: 1 = Not a problem at all, 2 = A small problem, 3 = A problem, 4 = A very big problem)

Challenge	1	2	3	4
Lack of knowledge				
Cost of implementation				
Lack of government support				
Limited access to technology				
Other (Specify)				

14. How well do you think the following water-saving methods would help you save water on your farm? (Use the following scale :1=Would not help at all, 2 = Would help a little, 3= Would help, 4 = Would help a lot)

Water-saving methods	1	2	3	4
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Drip Irrigation (watering plants slowly through small pipes)				
Soil moisture monitoring (checking how wet or dry the soil is)				
Mulching (covering soil with leaves or grass to keep it wet)				
Efficient irrigation scheduling(planning when and how much to water)				
Use of drought-resistant crop varieties(growing crops that need less water)				

15. How do you feel about the cost of using water-saving technologies on your farm? (Use the following scale: 1 = Cheap, 2 = Reasonable, 3 = Expensive, 4 = Very expensive)

Cost of water-saving methods	1	2	3	4

SECTION J: Impact of Climate Change on Water Availability (How Changing Weather Affects Access to Water for Farming)

J1. How have the changes in weather affected the amount of water available for your farming activities in recent years? **(Please select all that apply):**

Impact on Water Availability	Tick
More dry periods or droughts (less rain)	
More floods (heavy rains)	
Hotter days and nights	
Lower water levels in rivers, wells, or dams	
Boreholes are drying up or producing less water	

No changes noticed	
Other (please specify):	

J2. How have changes in weather affected the amount of crops you harvest?

Effects on Crop Production	Tick
My crops produce less than before because of the weather changes	
My crops produce more than before because of the weather changes	
My crops produce the same amount as before despite the weather changes	
I am not sure if the weather changes have affected my crops	

J3. What have you done on your farm to deal with changes in weather and water availability?

Adaptations to Changes	Tick
Changed crops to ones that need less water	
Changed crops to ones that can handle more heat	
Adjusted planting or harvesting times	
Collected and stored more water (e.g., using tanks or reservoirs)	
Invested in water-saving methods (e.g., drip irrigation, mulching)	
No changes made	
Other (please specify):	

SECTION K: WATER USER ASSOCIATION

Important Note: Non-WUA members: Answer only Questions K1 to K5.

WUA members: Answer all Questions K1 to K19.

K1. Do you know about Water User Association (WUA)? (If no, skip to question K3)

Yes	No
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K2. If the response to question K1 is yes, are you a member of a water user association?

(If yes skip to question K6)

Yes	No
-----	----

K3. If you are not a WUA member, would you be interested in joining the association?

Yes	No
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K4. If you are not interested in joining a WUA, what are the main reasons?

(Please select all that apply)

Reasons for not joining a WUA	Tick
I don't know enough about WUA or its benefits	
The membership fees are too high	
I had bad experiences in the past	
It's hard to join	
The WUA is too far away	
I'm happy with how I manage water now	
I don't have enough time	
Other (please specify):	

K5. If you are interested in joining a WUA, what would make you more likely to join?

(Please select that apply)

Reasons to join a WUA	Tick
Getting more information about what WUAs do	
Lower membership fees	
Better access to water and more reliable supply	
Access to training and learning opportunities	
Better management and clear rules	
Financial support or help with costs	
Other (please specify):	

SECTION N: PATHWAY 2 (FARMER-LED IRRIGATION: OWN IRRIGATION)

N1. What source of water do you use for irrigating your crops? **(Please select all that apply)**

Water source	Tick
River (Answer N2)	

Borehole	
Municipal water	
Other (please specify):	

N2. Where is your farm located along the river that you use for water? **(Please select all that apply)**

Position of farm from water source	Tick
Upstream (near the river)	
Midstream (Along the middle section of the river)	
Downstream (Away from the river)	

N3. How does the water from the source reach your field? **(Please select all that apply)**

Water delivery method	Tick
Gravity	
Diesel pump	
Electric pump	
By hand (e.g., buckets, watering cans)	
Open canal flow	
Other (please specify):	

N4. Which irrigation system are you using? **(Please select all that apply)**

Irrigation system	Tick
Sprinkler	
Drip	
Micro	
Furrow	
Flood	
Bucket/ watering can	
Centre pivot	
Other (please specify):	

N5. What influenced your decision to use the irrigation system mentioned in question N4? **(Please select all that apply)**

Factors that influence the choice of the irrigation system	Tick
Cost	
Ease of use	
Advice from other farmers	
Availability of resources	
Other (please specify):	

N6. What benefits have you noticed from using the irrigation system you selected in question N4? **(Please select all that apply)**

Benefits	Tick
Increased crop yields	

Reduced risk of crop failure	
Extended growing season	
Greater control over when and how much I water my crops (flexibility in crop management)	
Improved water use efficiency (less water wasted)	
Other (please specify):	

N7. What challenges have you faced with the irrigation system you are using? **(Please select all that apply)**

Challenges	Tick
Water leaks	
Pipes get blocked	
High costs for fuel or electricity to run the system	
High costs of installing the system	
It's hard to maintain or repair the system	
Not enough water pressure or flow to irrigate properly	
Other (please specify):	

N8. Who provided the selected irrigation system? **Please select all that apply)**

Funder	Tick
Government	
NGO	
Local municipality	
Own funds	
Other (please specify):	

N9. How much did it cost to install the irrigation system? R.....

N10. What specific challenges do you face with managing water while paying for your own irrigation system? (This question is only for respondents who selected "Own funds" in N8.)

Challenges with self-funded irrigation	Tick
Difficulty finding enough water sources (e.g., boreholes or rivers drying up)	
Poor water quality affecting crops (e.g., salty water, polluted water)	
Problems getting or keeping water rights (e.g., government	

rules, disagreements over access)	
Conflicts with other farmers or communities over water use	
Other (please specify):	

Thank you for your participation

