International Journal of Food Science and Agriculture, 2025, 9(4), 430-440
https://www.hillpublisher.com/journals/jsfa/
ISSN Online: 2578-3475
ISSN Print: 2578-3467

Assessment of Agricultural Water Management Practices Under Rain-fed and Farmer-led Irrigated Systems in South Africa

E. J. Mwendera[1,*], L. S. Mudau[2], F. Onyando[3], G. M. Senyolo[2], B. Serote[2], N. B. Nemakonde[2], N. M. Mamogobo[3], L. Nhamo[4]

[1]Clovita Consulting Services, Pretoria 0184, South Africa.
[2]Faculty of Sciences, Tshwane University of Technology, Pretoria 0001, South Africa.
[3]Department of Agricultural and Rural Engineering, University of Venda, Thohoyandou 0950, South Africa.
[4]Water Research Commission of South Africa (WRC), Lynnwood Manor, Pretoria 0081, South Africa.

How to cite this paper: E. J. Mwendera, L. S. Mudau, F. Onyando, G. M. Senyolo, B. Serote, N. B. Nemakonde, N. M. Mamogobo, L. Nhamo. (2025). Assessment of Agricultural Water Management Practices Under Rain-fed and Farmer-led Irrigated Systems in South Africa. *International Journal of Food Science and Agriculture*, 9(4), 430-440.
DOI: 10.26855/ijfsa.2025.12.017

Received: November 30, 2025
Accepted: December 26, 2025
Published: January 22, 2026

Corresponding author: E. J. Mwendera, Clovita Consulting Services, Pretoria 0184, South Africa.

Abstract

An assessment of agricultural water management (AWM) practices was conducted in Gauteng and Limpopo provinces of South Africa. The study focused on AWM practices under rainfed farming and farmer-led irrigation systems. Data were collected using focus group discussions (FGDs), structured questionnaires, and a stakeholder workshop. It has been shown that there are promising investment opportunities in the country based on the AWM practices under rain-fed and irrigated systems. The rainfed farming system is a high-priority area for investment with potentially large benefits, as it involves the majority of the small-scale farmers in the country. The country should develop specific policies and implement long-term investment programmes to work with local communities to restore degraded landscapes and move to sustainable resource management. Farmer-led irrigation development (FLID) is a very important driver of increased food production, especially for urban markets. It requires very little financial investment by governments, as the input and output value chains are largely driven by the private sector. Individualised irrigation technologies are easier to target at women, youth, and others who otherwise may be left out in the other farming systems. The farmers can be supported through special subsidies and focused capacity strengthening, which requires consultations and experimentation with these farmers to make sure those targeted really benefit.

Keywords

Agricultural water management; rainfed farming; farmer-led irrigation; irrigation water sources; conservation agriculture

1. Introduction

Agricultural water management (AWM) comprises a suite of water management practices in agriculture, including but not limited to watershed management, water capture, storage, conveyance, and application. This holistic focus is strategic because the sustainable and productive water management in agriculture requires attention to several factors, including inter alia, climate change and variability, crop selection, animal nutrition, maintaining ecosystem goods and services, and soil quality. For example, irrigation alone will not guarantee increased crop productivity on nutrient-poor soils; pests and diseases can severely diminish water productivity; and changes in precipitation or temperature may render some agricultural options untenable [1]. AWM includes capture and storage (in dams, in groundwater) as well as the drainage of any water used for agriculture (crops, livestock, fish); lifting and transporting water from where it is captured to where it is used for agricultural production or removing excess water from where agriculture is practiced; and in-field application and management of water, including land management practices that affect water availability to crops [2]. Thus, AWM encompasses the management of water used in crop production (both rainfed and irrigated), livestock production, and inland fisheries. Improved AWM in these production areas is crucial for global food security and poverty reduction[1]. Namara et al. [3] identified AWM practices into three main groups of technologies, namely, technologies for water control and storage, technologies for water lifting and conveyance, and field water application technologies. They further argued that in-field application and management of water and land are the common denominators, regardless of the water source, and are critical elements of all agriculture. Therefore, AWM is essential for successful agricultural production.

Rainfed agriculture, which covers approximately 80% of the world's cultivated lands and contributes significantly to 60% of total crop production, is a fundamental agricultural practice reliant solely on natural rainfall as its water supply [4, 5]. Beyond its agricultural role, rainfed farming plays a pivotal part in global food security and the sustenance of communities worldwide [6, 7]. It is responsible for 99% of the production of the main cereals, such as maize, millet, and sorghum in Sub-Saharan Africa [8]. It is estimated that 93% of the African population relies on rainfall for survival, while about 70% of citizens of the Southern African Development Community (SADC) depend on rainfed agriculture for their livelihoods [9]. Productivity growth in rainfed farming can be accelerated if controlled water can be added to the system. This agricultural practice serves as the major source of staple food production for the majority of rural inhabitants in sub-Saharan Africa (SSA) [10].

Rainfed agriculture is prevalent in South Africa, particularly among small-scale farmers who utilize the majority of cultivated land [11]. This practice supports over 13 million people across approximately 4 million farms, playing a vital role in the income of rural households and occupying about 30% of the country's arable land [12]. However, South Africa faces significant water-related challenges due to its low annual rainfall average compared to the global average [13]. Hartley et al. [14] reported that approximately 80% of South African crop production is rainfed, with irrigated crops accounting for only 20%.

Farmer-led irrigation development (FLID) has gained increasing importance in Africa over the last 20 years and is identified as the dominant process driving agricultural water expansion in Africa [15]. This sector comprises individuals and small groups who make their investments to advance irrigation and AWM practices. These are mostly small-scale, market-oriented producers, typically farming horticultural crops for urban markets [16]. FLID has expanded rapidly in the West, East, and Southern African regions, and studies have shown that the areas under AWM are likely much larger than what is officially recorded [17]. FLI technologies and practices vary across the nine countries but include creating shallow groundwater with tubewells or open dug wells, lifting water from rivers and streams using either manual or motorised pumps, ex-situ water harvesting in ponds or small dams, adoption of drip and sprinkler irrigation technologies, and gravity-based systems tapping small streams [16].

Poor AWM and agronomic practices drive land degradation and biodiversity loss due to the expansion of rainfed systems into marginal lands and forests. Therefore, this study aimed to understand the complex landscape of the AWM practices under rain-fed and farmer-led irrigation systems in the country.

2. Materials and Methods

2.1 Study location

The study was conducted in the Limpopo and Gauteng Provinces. The Limpopo Province, which is located in the far northern part of South Africa, links the country with the rest of Southern Africa. The province comprises five districts, namely Sekhukhune, Mopani, Capricorn, Waterberg, and Vhembe (Figure 1).

These districts are made up of three distinct climatic regions: the low-veld (arid and semi-arid) regions, the middle veld, high-veld, and semi-arid regions [18]. In the context of agriculture, the Limpopo Province is described as the "Garden of South Africa" because of its rich production of fruits and vegetables [17]. The predominantly rural province has been identified as the second-poorest province in the country after the Eastern Cape province [19, 20]. However, despite the availability of varied water sources such as springs, boreholes, canals, and rivers, communities in the province have been suffering because of erratic water supplies [21, 22].

As a result, small-scale agriculture has become intensely reliant on rainfall, making it highly vulnerable to the impacts of climate change [23]. High levels of inter-annual precipitation variability led to regular droughts and vulnerability with regard to food and water security [22].

[1] https://eos.com/blog/agricultural-water-management/

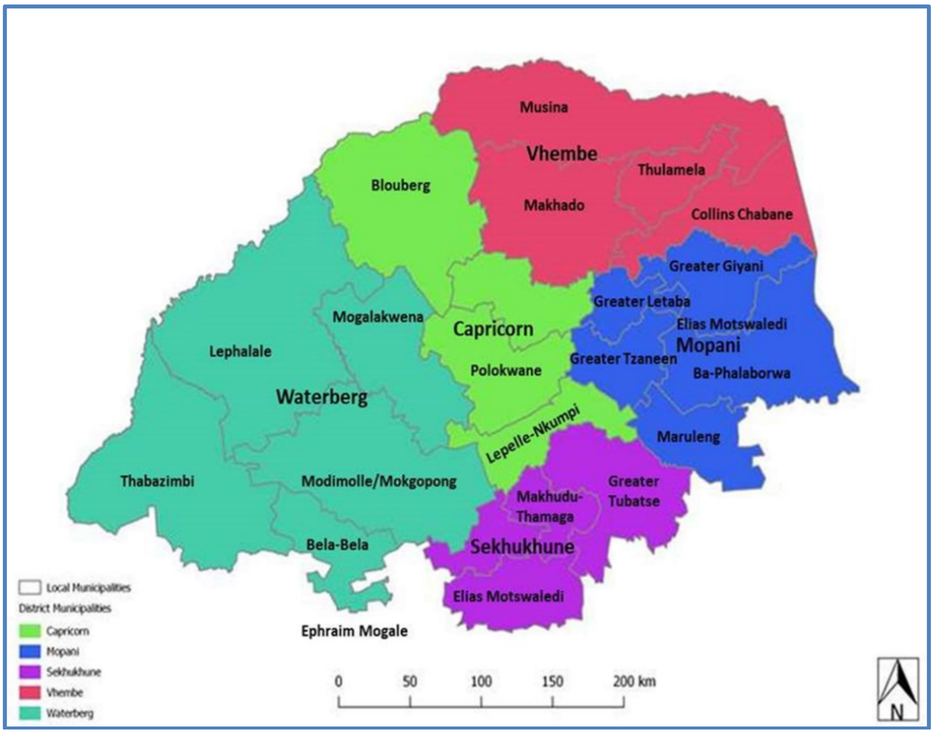

Figure 1. Map of the Limpopo Province. (Source: Serote et al., 2021)

Gauteng Province is both the richest and the smallest province in South Africa [24]. Unlike the Limpopo Province, Gauteng Province (Figure 2) is divided into three metropolitan municipalities (City of Ekurhuleni, City of Johannesburg, and City of Tshwane) and two district municipalities (Sedibeng and West Rand). The two districts are further divided into six municipalities: Emfuleni, Lesedi, Merafong City, Midvaal, Mogale City, and Rand West City.

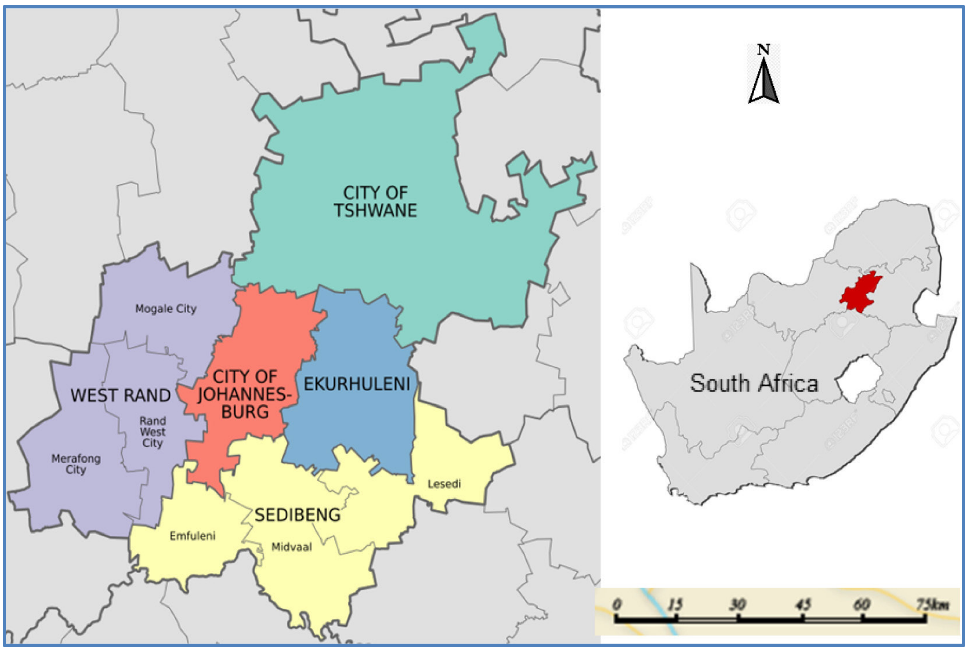

Figure 2. Map of the Gauteng Province. (Source: Nhamo et al., 2021)

This province, located in the central north-eastern part of the country, is one of the most populated provinces with an estimated population of around 12.3 million people [25]. However, 22.4% of the country's total population resides in poor peri-urban areas within the province, enabling diversity in the types of farming systems and levels of agricultural production [26]. This huge population tends to place water resources under stress due to extensive human activities such as agriculture, industry, and mining that generate waste and negatively impact the environment and water quality in particular [26]. In the context of water use in agriculture, some farmers use wastewater released from the sewage system as a water source while others rely on rivers, dams, boreholes, and rain. Therefore, the transformation of identified farming systems in the two provinces through AWM is essential to ensure the sustainable use of available water.

2.2 Data collection and analysis

Face-to-face interviews were conducted to collect data for rainfed and irrigated farming systems. Data were also collected through a structured questionnaire from farmers. The study used focused group discussions (FGDs) with the relevant stakeholders. A questionnaire was developed and administered to the identified key stakeholders. The purpose of the focus group discussion was to identify and gather information about the farmers under the rainfed and farmer-led irrigation systems. In the Limpopo Province, FGDs were conducted with stakeholders from the Department of Agriculture, Land Reform and Rural Development (DALRRD) in Thulamela Municipality and the provincial stakeholders from DALRRD in Limpopo Province. In the Gauteng Province, the focus was on the Tshwane municipality, where consultations were held with farmers, managers, and government officials from the Department of Agriculture, Water, and Sanitation.

A stakeholder workshop was organised as part of the FGDs process. The objective of the stakeholder workshop was to solicit inputs from key stakeholders on the policy, governance and institutional systems for creating an enabling environment for the implementation of the AWM practices in the country. Apart from the questionnaire, data and information on AWM practices in the country were obtained through a desktop review of various reports and documents from key institutions.

The collected data were analysed using the Statistical Package for the Social Sciences (SPSS 22), Statistical Software for Data Science (STATA 15), and ATLAS.ti. Descriptive statistics were employed to describe the various AWM practices and processes under the two farming systems.

3. Results and Discussion

3.1 Introduction

The assessment focused on practices related to agricultural water under rainfed and irrigated farming systems. The study focused on AWM practices under rainfed farming and farmer-led irrigation systems.

3.2 Rainfed farming systems in South Africa

Rainfed agriculture is a predominant form of farming in South Africa, whereby approximately 80% or more of the land that is cultivated is used for rainfed agriculture. There are a number of farmers practising rainfed farming across the country. However, the details of rainfed farming are scanty as the DALRRD does not have records and data regarding these farmers and as to where they are located in the municipalities, as well as the crops they grow. Generally, the land size for most rainfed farmers is between 1 and 3 ha. However, there are some rainfed farmers who have a larger land size greater than 5 ha. The most common crops which these farmers normally grow include maize, sorghum, tobacco, cotton, beans, nuts, and sunflowers. The available data show that the total land under the rainfed farming system in the country is 10,779,615 ha, which is 80% of the agricultural land. Under a rainfed farming system, supplemental irrigation is practised as a mitigation measure against intra-seasonal droughts.

One of the major challenges faced by rainfed farmers is climate change. The problems associated with climate change include: rainy season starting later than usual; unreliability and unpredictability of rainfall; high temperatures that cause drought; and heavy rainfalls that damage crops. Some of the small-scale farmers practice rainwater harvesting using jojo tanks for both irrigation and home consumption.

In Kanana, Hammanskraal, rainfed farmers rely on hand-dug wells for supplementary irrigation during dry periods (Fig. 3). In the absence of rainfall, they manually draw water from the wells using buckets. Although the wells may appear shallow in photographs, they are actually quite deep. A rope is tied to one of the buckets, allowing it to be lowered into the well and pulled back up with ease. The water is then transferred to another bucket, which is carried to the field for irrigation purposes (Fig. 4).

Figure 3. Hand-dug well in Kanana, Hammanskrall, Pretoria.

Figure 4. Rainfed farmers using water collected from a hand-dug well for supplemental irrigation in Kanana, Hammanskrall, Pretoria.

3.3 Farmer-led irrigation systems

3.3.1 Irrigation water sources

The study also assessed the water resources that farmers use for irrigation in the country, as these influence the irrigation systems and the AWM practices. Irrigation water resources data were obtained from the Department of Water and Sanitation (DWS). The data were analysed to determine the amounts of water issued by the DWS to farmers for irrigation at the regional and district municipality levels. The data were also analysed to determine the main water resource types for irrigation in the country, and the project team managed to obtain irrigation water data from the DWS.

Farmers who want to irrigate their crops are obliged to obtain permits from the DWS to obtain water from various sources for their irrigation systems. The volumes of water per year issued by the DWS to irrigation farmers at the regional level are presented in Figure 5. The largest volume is issued in the Mpumalanga region, which is a reflection of the high irrigation production in the region.

The largest mean volume of irrigation water issued at a district municipality level is in Frances Baard District Municipality in the Northern Cape Province (Fig. 6). The water resource type with the largest number of irrigation farmers at the national level is schemes, followed by wetland (Fig. 7). This means the largest number of farmers obtain their irrigation water through scheme sources.

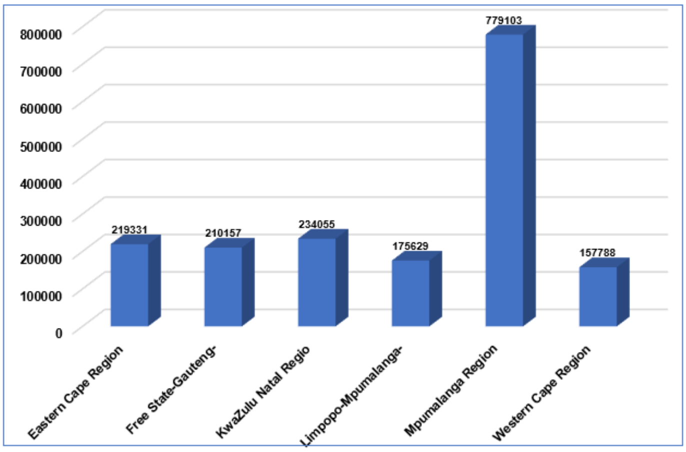

Figure 5. Mean volume of water issued for irrigation at the regional level. (Data Source: [27])

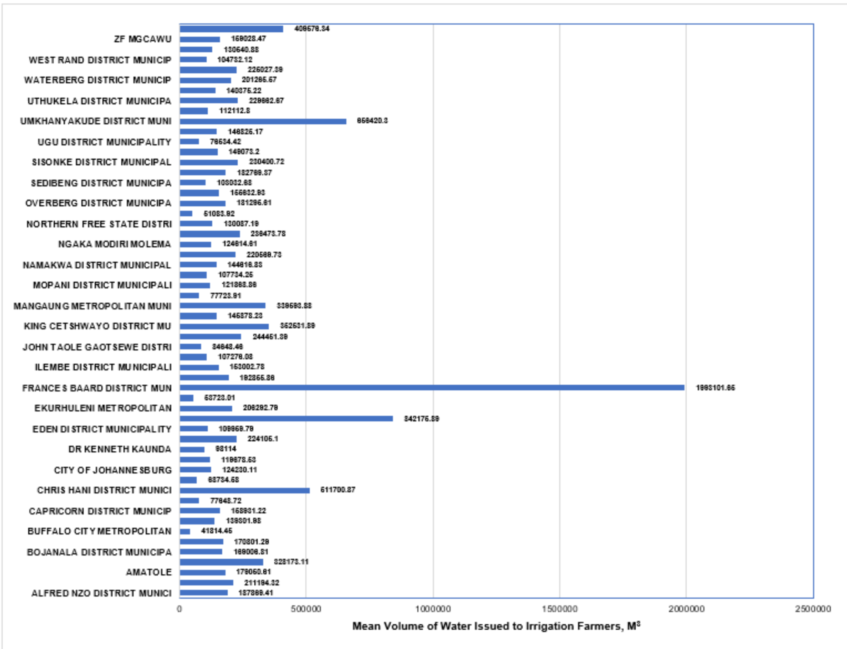

Figure 6. Mean volumes of water issued to irrigation farmers at the District Municipality level. (Data Source: [27])

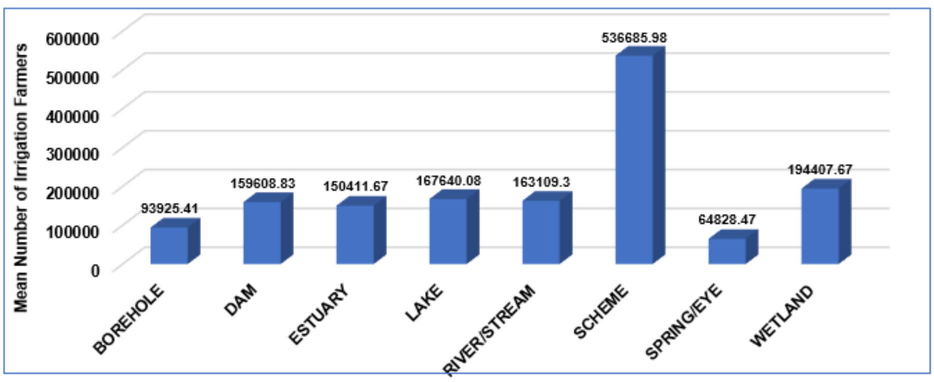

Figure 7. Mean number of irrigation farmers sourcing water from the different resource types in the country. (Data Source: [27])

The largest mean volume of irrigation water at the regional level is in the scheme, and Mpumalanga Region has the largest volume, followed by Free State, Gauteng Region, and Northern Cape Region (Fig. 8).

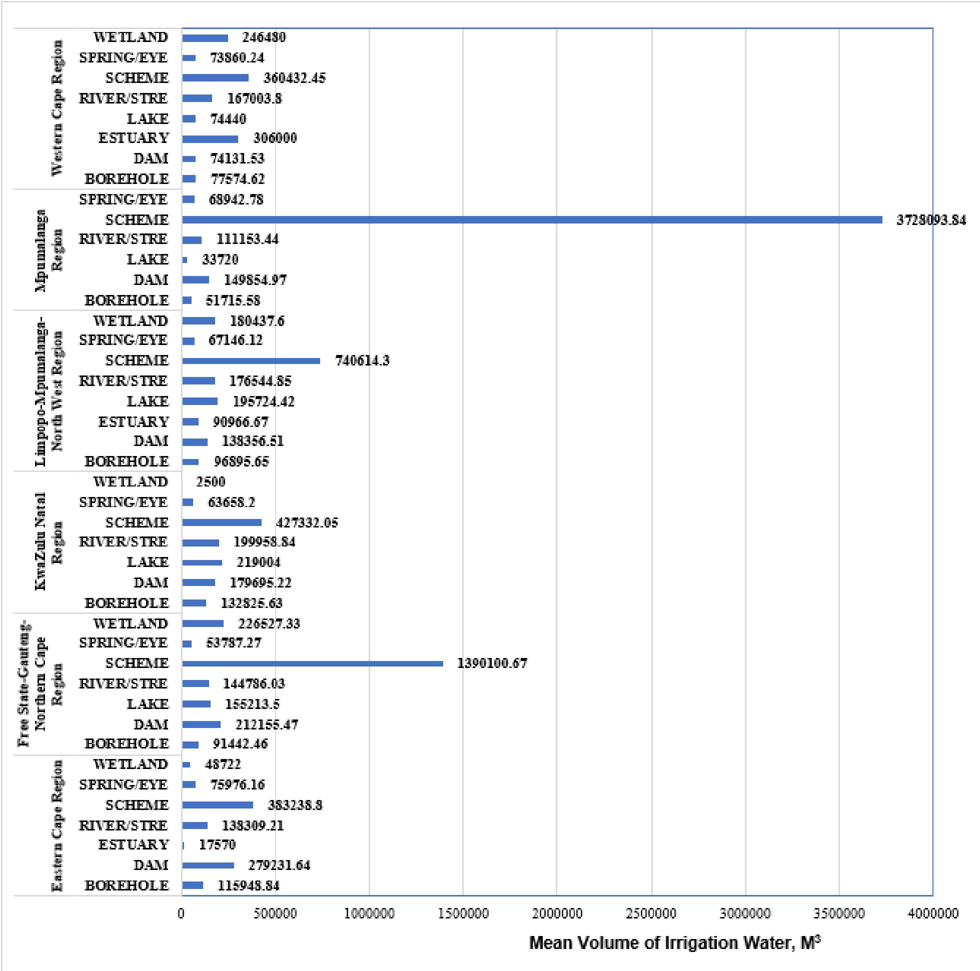

Figure 8. Mean volumes of irrigation water sources at the regional level. (Data Source: [27])

3.3.2 Farmer-led irrigation practices

The FLID farmers are independent farmers who play a role in improving their water use for agriculture by taking the lead in establishing and improving it through their own initiatives. The majority of these farmers get water from the rivers, groundwater (borehole), and municipal water, and they use different ways/equipment to irrigate. The characteristics of these farmers include that they use watering cans, buckets, drip, and sprinkler irrigation to irrigate their crops. Furthermore, the majority of the farmers practising farmer-led irrigation have a land size of less than 1.5 ha, and they practice both conventional and conservation agriculture (minimum tillage, mulching, and different cropping systems). These farmers plant a variety of crops each season due to access to water to irrigate, but the majority of the crops planted include maize, beans, and vegetables (tomatoes, onions, peppers, carrots, lettuce, spinach, and cabbage).

While FLID varies in its appearance, there are several irrigation practices developed through FLID that are widespread in the country, including irrigation from earthen canals in mountainous areas, the use of shallow groundwater in valley bottoms, petrol pump irrigation from open water bodies, and peri-urban agriculture using wastewater. The study has shown that the system involves practices such as diversion of streams using earthen main canals carrying the water from the stream to the field, often referred to as the furrow. Usually, along a stream, several diversions are constructed, sometimes creating networks of interlinked canals on the hill slopes. Water is predominantly used for intensive production of marketable vegetables, but also for supplementary irrigation of staple crops, particularly in times of drought.

Valley bottoms in dry regions can be relatively wet due to their shallow groundwater levels. Over the past 40 years, there has been a gradual shift in the use of such valleys from dry-season grazing to intensive dry-season vegetable production. During the wet seasons, they are more commonly used for rice production. Supplementing available soil water moisture, water is collected by manually scooping it from shallow dug wells and through the use of pumps on such wells [28]. After the rainy season, farmers try to drain off excess water as soon as possible, while drains are closed later in the season to hold on to as much water as possible to sustain growth in the dry season.

Petrol and diesel pumps have emerged as an irrigation technology for smallholder farmers to pump water from open water bodies, such as lakes and rivers, for intensive horticultural production. In some cases, small pumps are used to draw water from reservoirs behind dams in order to irrigate larger areas upstream of the dam rather than by gravity downstream [29]. In other cases, horticultural production by means of petrol pumps provides an alternative to declining fisheries, hence an important alternative economic opportunity for young people in the area [30].

Small-scale horticultural producers in cities and peri-urban areas often make use of waste water – diluted or raw – creating serious health risks both for those handling the water and for consumers buying the products of such irrigation [28]. Watering cans are commonly used for this type of irrigation. Though laborious, this technology often suffices for the generally small plot sizes in the city, which are mostly limited to between 0.01 and 0.02 ha per farmer [28]. Motorised pumps are increasingly being used, especially where farmers can share a pump and where distances between the water source and the fields are large. Even in these cases, farmers continue to use the watering cans, drawing from a reservoir on the farm that is filled by the pump. In all these cases, FLID is strongly oriented towards producing crops for the market, and almost 40% of irrigators adopt intensive production practices using fertilisers and improved seeds, while only 10% of non-irrigators do so [31].

An increasing number of small-scale farmers are independently utilising irrigation. They purchase or rent irrigation equipment and source water from nearby dams, rivers, or underground, operating without a licence or interference from public agencies or water user associations. Most of the farmers using private or farmer-led irrigation are females operating on an average of 4 ha of land. Some are using community land such as school and church gardens producing leafy vegetables (cabbage, spinach, lettuce, etc), tubers (potatoes, sweet potatoes), and root vegetables in Gauteng Province. Most of the farmers are using crop rotation. Very few farmers received AWM training, so there is a need for training.

Most farmers source water from dams, boreholes, and municipalities. Then, a sprinkler irrigation system is used for irrigation, as they believe that it covers all the plants and saves time. Some sources their water from the wells. The main challenges faced by farmers are theft of boreholes and damage to boreholes due to lightning during heavy rainfalls, and low supply of water from the municipality. On average, a typical farmer irrigates 4 times a week and pays R600 per month for water. In addition, the level of food security is low, and it can improve when access to irrigation water is improved.

The individualisation of AWM has been progressing for several decades in SSA, where most irrigation now relies on privately owned wells. Some farmers are using wells and ponds as a source of irrigation water for their crops. Water is collected through containers or pipes from a source to the field. Crops produced and irrigated through these methods are sweet potatoes, root vegetables, and leafy vegetables. Figure 9 shows a broken-down borehole, while Figure 10. shows a farmer drawing water for irrigation from a well in Gauteng due to his boreholes not working.

Figure 9. A broken-down well in Winterveld, Gauteng Province.

Figure 10. A farmer drawing water from a well in Winterveld, Gauteng Province.

In addition, most of the small-scale farmers are using municipal water for irrigation. The water is drawn from home taps through the use of containers or pipes to irrigate their fields. Crops produced are mainly leafy vegetables (both exotic and indigenous), tubers (carrots, potatoes, etc.), and chillies.

Some FLI farmers have tractors (Fig. 11) used for ploughing, tilling, disking, harrowing, planting, and similar tasks on their irrigation farms. The furrow irrigation system (Fig. 12) is also common among small-scale irrigators. The fact that most of these farmers operate mostly outside the government, and they are not easy to identify and map, because they are not documented. In addition, the irrigated area established by farmers is not included in the government's database, and FLID, which is primarily small-scale and not formal, falls into the group of farmers who are rarely recorded [32].

Figure 11. Water tank and tractor at an irrigation farm, Malskop, Makhado Municipality.

Figure 12. Furrow irrigation system at an irrigation farm, Malskop, Makhado Municipality.

These irrigators operating outside formal irrigation schemes often lack access to the institutional and financial support systems. Such support includes agricultural advice, training, input support, and infrastructure development. Furthermore, the FLID farmers use their home savings, pension funds, and income from other sources to support the farms. One of the challenges that the farmers face is poor water quality or polluted water from rivers, the lack of access to extension services, capacity building, and resources such as fertilisers. Climate change and variability (heat) affect crop development, leading to crop failure.

4. Discussion

One of the major challenges faced by rainfed farmers is climate change. The problems associated with climate change include: rainy season starting later than usual; unreliability and unpredictability of rainfall; high temperatures that cause drought; and heavy rainfalls that damage crops. Rainfed farmers are likely to invest in improved AWM practices if they see real benefits within a fairly short time. While the government is supporting the farmers in various ways, the policies of the government should support the adoption of improved soil and water management in rainfed agricultural systems, implemented through long-term investment programmes in close collaboration with local communities.

Most of the rainfed farmers who depend on rainwater for irrigation are those who produce maize, soyabean, groundnuts, dry beans, sorghum, etc., and the others produce indigenous vegetables (some grown by themselves). The farmers also practice supplemental irrigation using furrow and in-field rainwater harvesting. Their water management practices include conservation agriculture, rainwater harvesting, pasture farming, mixed farming, and wetland farming.

Farmer-led irrigation is widespread in the country. While the government has no specific policies or programmes to support farmers' own irrigation investments, the government provides more support for farmers' investments in technologies such as pumps, drip, and sprinkler systems.

Most farmer-led irrigators operate outside formal irrigation schemes and often lack access to the institutional and financial support systems. Such support includes agricultural advice, training, input support, and infrastructure development. Furthermore, the FLID farmers use their home savings, pension funds, and income from other sources to support the farms. FLID farmers face poor water quality or polluted water from rivers, and they have limited access to extension services, capacity building, and resources such as fertilisers.

Although FLID is largely invisible to policymakers, it is a potential game-changer for millions of small-scale farmers. Investments can generate multiple synergies and impacts by improving farmers' livelihoods, enhancing the food security of consumers, creating jobs, and promoting economic growth. This high-priority farming system has a lower cost per farmer than large-scale irrigation investments, begins generating returns immediately, and can leverage private investments from farmers and private firms, and does not require large financial investments by the government.

The actions needed to support rapid scaling out of FLID include ensuring affordable access to irrigation technologies, ensuring there is a level playing field for private firms to market and even manufacture locally, irrigation technologies; and encouraging local financing institutions to provide credit to enable small-scale, including women and youth, to purchase equipment.

5. Conclusion

The study focused on AWM practices under rainfed farming and farmer-led irrigation systems. The study used the provinces of Limpopo and Gauteng as case studies. It has been shown that there are promising investment opportunities in the country based on the AWM practices under rain-fed and irrigated systems. The rainfed farming system is a high-priority area for investment with potentially large benefits, as it involves the majority of the small-scale farmers in the country. The country should develop specific policies and implement long-term investment programmes to work with local communities to restore degraded landscapes and move to sustainable resource management. FLID is a very important driver of increased food production, especially for urban markets. It requires very little financial investment by governments, as the input and output value chains are largely driven by the private sector. Individualised irrigation technologies are easier to target at women, youth, and others who otherwise may be left out in the other farming systems. The farmers can be supported through special subsidies and focused capacity strengthening, which requires consultations and experimentation with these farmers to make sure those targeted really benefit.

Acronyms and Abbreviations

AWM	Agricultural Water Management
DALRRD	Department of Agriculture, Land Reform and Rural Development
DWS	Department of Water and Sanitation
FGDs	Focus Group Discussions
FLID	Farmer-led Irrigation Development
SADC	Southern African Development Community
SSA	Sub-Saharan Africa

Funding

The research was funded by the Water Research Commission of South Africa (Project No.: C2023/2024-01240).

References

[1] Jones PG, Thornton PK. Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. Environ Sci Policy. 2009;12:427-437. doi:10.1016/j.envsci.2008.08.006.

[2] Merrey D, Regassa Namara, de Lange Marna, et al. Agricultural water management technologies for small-scale farmers in Southern Africa: an inventory and assessment of experiences, good practices and costs. Final Report. Pretoria: IWMI; 2006. USAID/OFDA/SARO Order No. 674-O-05-05227-00; FAO LOA No. PR 32953.

[3] Namara RE, Hanjra MA, Castillo GE, et al. Agricultural water management and poverty linkages. Agric Water Manag. 2010;97:520-527. doi:10.1016/j.agwat.2009.10.019.

[4] Qin W, Wang D, Guo X, et al. Productivity and sustainability of rainfed wheat-soybean system in the North China Plain: results from a long-term experiment and crop modelling. Sci Rep. 2015;5:17514. doi:10.1038/srep17514.

[5] Liu Z, Jin J. Review on rainfed agriculture and rainwater harvesting techniques. Adv Biol Sci Res. 2016;3:329-331.

[6] Devendra C. Rainfed agriculture: its importance and potential in global food security. Agric Sci J. 2016;2:4-17.

[7] Brouziyne Y, Chehbouni A, Abouabdillah A, et al. Making rainfed crops adapted to potential climate change impacts: modeling

sustainable options. E3S Web Conf. 2020;183:03002. doi:10.1051/e3sconf/202018303002.

[8] Wani SP, Rockström J, Oweis T. Rain-fed agriculture: unlocking the potential. Wallingford: CABI; 2009. (Comprehensive Assessment of Water Management in Agriculture Series; 7).

[9] Southern African Development Community (SADC). Regional indicative strategic development plan. Gaborone: SADC; 2003.

[10] Beyer M, Wallner M, Bahlmann L, et al. Rainfall characteristics and their implications for rain-fed agriculture: a case study in the Upper Zambezi River Basin. Hydrol Sci J. 2016;61:321-343. doi:10.1080/02626667.2014.964240.

[11] Mkuna E, Wale E. Smallholder farmers' choice of irrigation systems: empirical evidence from Kwazulu-Natal, South Africa and its implications. Sci Afr. 2023;20:e01688. doi:10.1016/j.sciaf.2023.e01688.

[12] Mkuhlani S, Crespo O, Rusere F, et al. Classification of small-scale farmers for improved rainfall variability management in South Africa. Agroecol Sustain Food Syst. 2020;44:7-29. doi:10.1080/21683565.2019.1646376.

[13] Mtyelwa C, Yusuf SFG, Popoola OO. Adoption of in-field rainwater harvesting: insights from smallholder farmers in Raymond Mhlaba Local Municipality, Eastern Cape Province, South Africa. S Afr J Agric Ext. 2022;50:81-100. doi:10.17159/2413-3221/2022/v50n2a13305.

[14] Hartley F, Gabriel S, Cullis J, et al. Climate uncertainty and agricultural vulnerability in South Africa. SA-TIED Working Paper 162. 2021.

[15] Lankford B. Viewpoint – The right irrigation? Policy directions for agricultural water management in Sub - Saharan Africa. Water Altern. 2009;2:476-480.

[16] African Union. Framework for Irrigation Development and Agricultural Water Management in Africa. Addis Ababa: African Union Commission; 2020.

[17] Cai X, Magidi J, Nhamo L, et al. Mapping irrigated areas in the Limpopo Province, South Africa. Colombo: IWMI; 2017. (IWMI Working Paper 172).

[18] Serote B, Mokgehle S, Du Plooy C, et al. Factors influencing the adoption of climate-smart irrigation technologies for sustainable crop productivity by small-scale farmers in arid areas of South Africa. Agriculture. 2021;11:1-17. doi:10.3390/agriculture11050420.

[19] Odiyo JO, Makungo R. Water quality problems and management in rural areas of Limpopo Province, South Africa. In: Brebbia CA, editor. Water Pollution XI. Southampton: WIT Press; 2012. p. 135-146.

[20] Chikozho C, Managa R, Dabata T. Ensuring access to water for food production by emerging farmers in South Africa: What are the missing ingredients? Water SA. 2020;46:225-233. doi:10.17159/wsa/2020.v46.i2.8241.

[21] Karodia AM, Khan S. South Africa enters a water crisis: Management, agriculture, public health considerations and government ineptitude are some of the causes for this grave dilemma. Asian J Agric Ext Econ Soc. 2015;7:1-18.

[22] Makaya E, Rohse M, Day R, et al. Water governance challenges in rural South Africa: Exploring institutional coordination in drought management. Water Policy. 2020;22:519-540. doi:10.2166/wp.2020.200.

[23] Shikwambana S, Malaza N, Shale K. Impacts of rainfall and temperature changes on smallholder agriculture in the Limpopo Province, South Africa. Water. 2021;13:1-16. doi:10.3390/w13202873.

[24] Chitakira M, Ngcobo NZ. Uptake of Climate Smart Agriculture in Peri-Urban Areas of South Africa's Economic Hub Requires Up-Scaling. Front Sustain Food Syst. 2021;5:1-13. doi:10.3389/fsufs.2021.706738.

[25] Nesamvuni E, Mpandeli S, Tshikolomo K, et al. The enabling geophysical agricultural environment for agriculture in Gauteng Province, South Africa. J Hum Ecol. 2016;54:59-69. doi:10.1080/09709274.2016.11906978.

[26] Mothetha ML. Evaluation of the impacts of municipal wastewater treatment on the receiving environment: a case study of the Olifantsvlei wastewater treatment plant in the Gauteng Province, South Africa [MSc dissertation]. Pretoria: University of South Africa; 2016.

[27] Department of Water and Sanitation (DWS). National State of Water Report 2023. Pretoria: DWS; 2024. Report No.: WII/IWRS/NSoW 2023.

[28] Muturi J, Oggema S, van Veldhuizen L, et al. Accelerating Farmer-led Irrigation Development: Theory and practice of the Smart Water for Agriculture in Kenya project. Nairobi: SWA Kenya, SNV Netherlands Development Organisation; 2019.

[29] de Fraiture C, Kouali GN, Sally H, et al. Pirates or pioneers? Unplanned irrigation around small reservoirs in Burkina Faso. Agric Water Manag. 2014;131:212-220. doi:10.1016/j.agwat.2013.08.010.

[30] Bosma L. 'You've got to pump it up': Analysis of the appropriation and utilization of petrol pumps for small scale horticulture in West-Uyoma, Kenya [MSc thesis]. Wageningen: Wageningen University; 2015.

[31] Studying African Farmer-led Irrigation (SAFI). Farmer-led irrigation development and investment strategies for food security, growth and employment in Africa. Manchester: The University of Manchester; 2018.

[32] Venot JP, Bowers S, Brockington D, et al. Below the radar: Data, narratives and the politics of irrigation in Sub-Saharan Africa. Water Altern. 2021;14:546-572.