# Agricultural Water Solutions in the Tuli Karoo Aquifer Area

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## SUMMARY

Irrigation development plays a pivotal role as a key drought and climate change adaptation measures, and is critical in increasing agricultural production and productivity, food security, incomes, and employment. In the Tuli Karoo Aquifer Area, shared among Botswana, South Africa Zimbabwe, irrigation is nonetheless limited. Although nearly seven percent of the Tuli Karoo Aquifer Area is cultivated, less than one percent of the land area is irrigated. Given the drive for greater food security and resilience, there may be an opportunity to expand irrigation in an efficient and sustainable way. This study aimed to improve the capacity of smallholder farmers to improve water and nutrient use efficiency using water and nutrient management tools in the Tuli Karoo Aquifer Area in Botswana and Zimbabwe. The tools used were the Chameleon (soil water sensor) and the Wetting front Detector (WFD). The chameleon sensor changes the display colour light to blue, green or red depending on the level of soil water in the soil, while the WFD is used to collect moving wetting front at a certain depth in the crop root zone as field capacity is reached. The drainage water can be extracted from the WFD and tested for nutrients. Since the drainage collected in the WFD is related to amount of irrigation water and nutrients applied in the soil, it gives an estimate of nutrient loss beyond the crop root zone.

Five major findings emerged from this research. First, farmers learned to make better crop management decisions that improved water use, labour productivity, yields and income under the prevailing soil and irrigation systems, providing farmers with an adaptive learning environment to improve their decision making and understanding in agricultural water management. Second, significant irrigated water productivity improvement was realized for smallholder irrigation farmers in the Tuli Karoo Aquifer Area. Third, there was greater benefits of more water savings under flood irrigation method than drip, consistent with findings in Ramotswa Transboundary Aquifer and Zimbabwe. Fourth, yield and income improved following introduction of the management tools. Fifth, the feedback from the accelerated social learning experience of the farmers showed that the tools empowered farmers to understand soil water and nutrient dynamics and therefore adapted their management for the better through behavioural change and farmer were willing to pay for the tools and continue using them. Finally, initial findings in the Tuli Karoo Aquifer Area suggest substantial scope for broader application in geographies of similar conditions in Africa where water insecurity, food insecurity and irrigation are present.

To conclude, the use of management tools by smallholder farmers hold substantial potential to improving sustainable irrigated agricultural water use, crop water productivity and production, while minimizing adverse environmental impacts such as nitrate and pesticide pollution in semi-arid areas of Africa. Significant improvements in crop yield, and water and nutrient savings can be achieved by incorporating the management tools in smallholder irrigation schemes, thereby achieving food security and rural development. The viability of use of such tools in a crisis context like COVID-19 pandemic nonetheless depends on cooperation and capacity of farmers or farm supervisors and local extension officers for social learning.

# Contents

## List of Figures



## List of Tables

## List of Abbreviations

| | |
|---|---|
| ARDA | Agricultural and Rural Development Authority |
| AWM | Agricultural Water management |
| CESVI | "Cooperazione e sviluppo", Cooperation and development |
| DAFF | Department of Agriculture, Forestry and Fisheries |
| DWS | Department of Water and Sanitation |
| EMA | Environmental Management Agency |
| ET | Evapotranspiration |
| FAO | Food and Agriculture Organisation of the United Nations |
| GLEAM | Global Land Evaporation Amsterdam Model |
| OECD | Organisation for Economic Co-operation and Development |
| IWMI | International Water Management Institute |
| SPEDU | Selebi-Phikwe Economic Diversification Unit |
| TKAA | Tuli Karoo Aquifer Area |
| UNDP | United Nations Development Programme |
| WARMS | Water use Authorization & Registration Management System |
| WFD | Wetting Front Detector |

## 1. Introduction

***Importance of agriculture in Africa*** Agriculture is one of the sectors that support inclusive growth through exports and development of supply chains. Governments have recognised the pivotal role of irrigation development as a key drought and climate change adaptation measure, critical in increasing agricultural production and productivity, food security, income generation, and employment creation African Union (2020), revealed that adoption of irrigation and other Agricultural Water management (AWM) practices can positively contribute towards wealth creation and food security at households scale as well as on the general economy. This report further argues for more positive ripple effects, with economic multipliers derived from support industries, services and activities in the input and output value chains, wage labour demand, and the construction industry. Achieving African food security and sustainability of food production systems with resource intensification under AWM under increasing population of 2.7% per annum (OECD/FAO, 2016) becomes even more challenging under limited surface and groundwater resources. Smallholder farmers are important as they consists of more than 70% of farmers and contribute to more than 80% of food production in sub-Saharan Africa (OECD/FAO, 2016; Alliance for a Green Revolution in Africa, 2014; Badiane et al., 2011).

***Importance of improving irrigation yield and income in agriculture*** Sub-optimal management of irrigation water in irrigation schemes frequently leads to actual irrigated land being far below the designed command area. This results in a low return on public investment and reduced impact on farm livelihoods as irrigators being relatively 'new' to irrigation grapple to translate their water and nutrient inputs into optimal yields Irrigation is identified as the highest (> 80%) water use in the world, but necessary for achieving agricultural growth. Hence, irrigation water should be applied efficiently, particularly in arid areas. With limited water resources and climate change, improving the irrigation water use efficiency is essential for sustainability of irrigation system for both smallholder and commercial farmers in Africa. To improve irrigation water use efficiency, innovative tools such as the Chameleon (soil moisture) sensor and Wetting Front Detector (WFD) have been successfully tested in several environments in Africa but not yet scaled up to reduce risk of water and nutrient loss to millions of people. These tools[1] aim to create an adaptive learning environment leading to improved water and nutrient management practices of farmers resulting in enhanced crop and water productivity at the farm level. More recently, Pittock et al. (2020) reported deployment of in-situ soil monitoring tools with farmers that enhanced irrigation management practices at five schemes from 2014 in Mozambique, Tanzania and Zimbabwe

***The Project*** This work was undertaken in the context of a project entitled: The *Conjunctive Water Resources Management across borders in the SADC Region: Generating Principles through fit-for-purpose practice*. The project contributes to sustainable water management in the Southern Africa Development Community (SADC) Region, through transboundary cooperation on shared critical water resources. The broad objective of the project is to enhance the capacity in SADC and its member states to manage integrated groundwater and surface water resources. The project will seek to identify and apply innovative solutions for conjunctive water management in transboundary river-aquifer systems. In particular, the project will identify issues and solutions that support the achievement of equitable, sustainable and resilience-strengthening water use, based on conjunctive management through deriving lessons from in the Shire River-Aquifer (Malawi and Mozambique), Ngotwane River /Ramotswa Aquifer (Botswana and South Africa), and Tuli Karoo (Botswana, South Africa, Zimbabwe) Systems. Given the level of existing activities in the Shire and Ngotwane/Ramotswa, the project places primary focus on the identification and recommendation of policy changes likely to advance pursuit of conjunctive water management solutions in the shared Tuli Karoo Aquifer and associated surface waters.

[1] https://via.farm

***This report: enhancing irrigation efficiency at the farmer and irrigation scheme scales in the Tuli Karoo*** This document reports on work done in the Tuli Karoo Aquifer Area – i.e., the surface area under which the aquifer lies in three countries – to enhance on-farm water use and productivity through introduction of WFDs and chameleons in smallholder irrigated agriculture, where part of the produce is marketed. These tools were evaluated by comparison of water and nutrient management practice versus farmer practice managed fields for gravity feed flood and drip irrigation methods in southern Africa (Botswana and South Africa). The crops assessed included beans, green pepper and tomatoes, and the results are presented for these crops. The report contributes to *Action Track Goal: By 2030, 300 million small-scale agricultural producers in low- and middle-income countries enhance their resilience to a changing climate, including climate shocks and extreme events, increase household incomes and food security, and reverse ecological decline — in line with multiple SDG's* (Global Commission on Adaptation, 2020). Section 2 provides the description of the study site, context of agriculture in the Tuli Karoo Aquifer Area and the process of selecting the study sites. In section 3, the methodology is presented. Section 4, 5 and 6 presents the results, discussion and conclusions, respectively. The discussion includes comparison of results from Tuli Karoo with those from Ramotswa, and considers broader potential for use of such management tools in Africa.

## 2. Study area and site selection

Botswana, South Africa and Zimbabwe face a range of inter-related challenges, including climate change; water scarcity, water quality degradation, inadequate sanitation facilities, persistent poverty as well as increasing and competing demands for water resources, such as irrigation versus domestic and environment. In many instances, a solution to one challenge creates other negative externalities. For instance, irrigated agriculture bridges dry spells and droughts and has resulted in exponential increases in food production, but also disrupted functions of riverine ecosystems and attenuated flow in rivers. These challenges require improved water resources water use efficiency including irrigated agriculture to enhance climate-resilient food production in a way that minimizes environmental impacts. The sources of water resources in the aquifer area include well-fields, dams, water carriers, wastewater re-use and the deployment of other rainwater harvesting technologies.

***Connection of production systems and markets is essential for sustaining agriculture-based livelihoods***. Agriculture (livestock, smallholder crop production) is an important source of livelihoods in the Tuli Karoo Aquifer Area (Sithumule, 2014). Agricultural produce is marketed locally and nationally for income. The market stability is affected by water availability, which is in turn affected by climate variability. Smallholder farming, both rainfed and irrigated are common in Botswana and Zimbabwe. Agriculture, forestry and fisheries contribute about 35% to the economy of Musina Local Municipality (MLM IDP, 2019). According to 2011 statistics, nearly 20% of the households in Musina were involved in agricultural activities (StatsSA, 2011), while 59% of Beitbridge population (2012) were employed in the agricultural sector (ZimStat, 2012). Livestock farming is important, especially in the Botswana and Zimbabwe due to dry and arid climate of the Tuli Karoo Aquifer Area (Masundire et al., 2018; EMA, 2019). In 2015, maize produced by subsistence farmers in Bobirwa constituted 5% of total subsistence maize produced in Botswana in 2015, while commercial maize production in Botswana constituted 68% of total maize produced (Statistics Botswana, 2015). Despite having high numbers of livestock production in the Tuli Karoo Aquifer Area across the three countries, this study focused on improving water and nutrient efficiency in irrigated agriculture (EMA, 2019; MoFDP, 2006).

## 2.1. Rainfed and irrigated agriculture in the Tuli Karoo

***Agricultural areas were categorized into irrigated and rainfed.*** Agricultural areas were categorized into single, double and continuous crops depending on cropping intensities (IWMI, 2010). IWMI (2010) adopted FAO definition of area under agricultural water management for defining irrigated areas. In this classification, area under agricultural water management is divided in to three:

- Irrigated area
- Rainfed
- Water management- residual soil moisture management

***Less than one percent of Tuli Karoo Aquifer Area is irrigated***. The total irrigated area including irrigated double crop, irrigated single crop and irrigated-triple crop account about 0.6% of the study area (Figure 1 and Table 1). Nonetheless, the Water Managed- Non Irrigated type accounts for about 5.1% of the study area. Considering the Tuli Karoo System – i.e., the surface waters encompassing the Tuli Karoo Aquifer Area (Figure 1) – about 5.4% of the Water Managed-Non irrigated type is in Shashe sub-basin, 2.9% in Mzingwane and 2.9% is in Motloutse. This shows that Shashe is the wettest of all the subbasins in the aquifer system, with highest crop rainfed areas. Irrigated areas are predominately in Shashe, Mzingwane and Motloutse catchments.

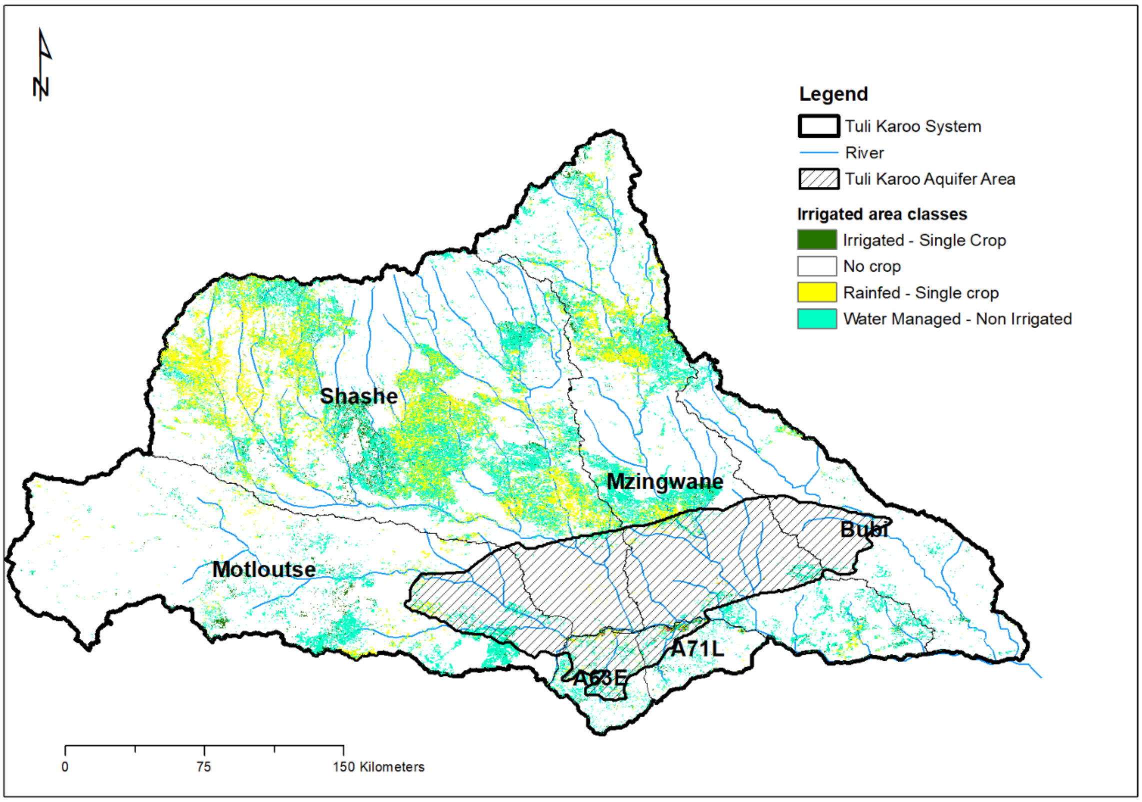


**Figure 1**. Irrigated and Rainfed Agriculture in the Tuli Karoo Aquifer Area and the Tuli Karoo System (Source of data: IWMI, 2010)

**Table 1.** Proportion of irrigated and rainfed crop areas in the Tuli Karoo System and Tuli Karoo Aquifer Area

| Land use | Proportion of Tuli Karoo System (%) | Proportion of Tuli Karoo Aquifer Area (%) |
|---|---|---|
| **Irrigated Single crop** | 1 | 0.6 |
| **Rainfed Single Crop** | 6 | 1.2 |
| **Water Managed- residual soil moisture management** | 10.5 | 5.1 |
| **Other land uses** | 82.5 | 92.8 |

Note: Other land uses include agroforestry or fruit trees and other non-agricultural land uses

***Irrigation is limited in the Tuli Karoo Aquifer Area*** Although nearly 7 percent of the Tuli Karoo Aquifer Area is cultivated, with less than 1% irrigated, there may be need to expand irrigation in an efficient and sustainable way for greater food security and resilience. Hence, the current project aims to enhance farmer irrigation knowledge and practice through use of water and nutrient management tools to improve water and nutrient use efficiency.

## 2.2. Agriculture: Crops and Livestock

### Crops

***Water use in Agriculture Crop Areas*** Based on irrigated land use mapping by IWMI (2010) using 16-day MODIS NDVI composites images (MOD13Q1), data of resolution 250m in Asia and Africa, and Global Land Evaporation Amsterdam Model (GLEAM) data (Martens et al., 2017), we estimated crop water use – Evapotranspiration (ET) – in irrigated and rainfed areas (Table 2). These were consistent with the irrigation water consumption volumes reported from several reports in the three countries (Botswana, Central Statistics Office, 2007, 2019; Masamba, 2009; Government of Zimbabwe, 2019).

**Table 2:** Crop water use under Irrigated and Rainfed areas, Tuli Karoo Aquifer Area in 2010 (Data source: IWMI, 2010; Martens et al., 2017)

| **Land Use** | **ET (mm)** | **Area ($km^2$)** | **Depth of water use (mm)** |
|---|---|---|---|
| Irrigated - single crop | 1,300.0 | 81.4 | 1,302.0 |
| Irrigated - double crop | 800.0 | 27.9 | 824.0 |
| Irrigated - triple crop | 400.0 | 9.5 | 421.0 |
| Sum | 2,600.0 | 118.8 | 1,120.0 |
| Water managed - non-irrigated - single crop | 37,000.0 | 675.2 | 36,996.0 |
| Water managed- non irrigated - double crop | 500.0 | 6.6 | 455.0 |
| Rainfed- single crop | 15,700.0 | 160.3 | 15,696.0 |
| Sum | 53,100.0 | 842.2 | 32,653.0 |

Note: Average annual rainfall is 250mm in the Tuli Karoo Aquifer Area.

***Area used for Irrigation and rainfed agriculture water use*** Total irrigated area in the Tuli Karoo Aquifer Area is approximately 12,000 ha. The largest area under irrigation is in South Africa (6,900 ha), followed by Zimbabwe (2,900 ha) and then Botswana (2,000 ha). Total rainfed area is just over 84,000 ha, across Zimbabwe (31,670 ha), Botswana (28,440 ha) and South Africa (24,780 ha). Overall, about 1 percent and 6 percent of the Tuli Karoo Aquifer Area is under irrigation and rainfed agriculture, respectively. Crops grown under irrigation include wheat, maize, beans, potatoes, lucerne, butternut, leafy vegetables and citrus fruits, while rainfed crops include maize and sugar beans and drought-tolerant small grains like sorghum, millet and rapoko.

***Water use in irrigation and rainfed agriculture*** Water consumption under single, double and triple crop irrigation (Table 2) was 2,548 mm (133 million $m^3$/a)based on 2017 evapotranspiration data (Martens et al., 2017). Assuming farmers typically apply an additional 25 percent water to cater for water lost beyond the root zone (MoAIWD, 2016), the irrigation water demand becomes 166 million $m^3$/a. This water use is comparable to 147 million $m^3$/a obtained from more recent reports from the three countries (Botswana, Central Statistics Office, 2007, 2019; Masamba, 2009; Government of Zimbabwe, 2019). The South African side is characterised by high tech irrigation systems that include the drip and dragon-line systems (short drip lines mounted on a mobile centre pivot) to use irrigation water efficiently (potential for 20-50 % water savings, reduces evaporation and wind drift), especially in large commercial farms (Dragon-Line Southern Africa (Pty) Ltd, 2018). Water efficiency in irrigation in the aquifer area is key to protection of water resources, as both smallholder and commercial farmers reported to irrigating twice or thrice a day during very hot months e.g., October, to avoid excessive crop heat-stress. This results in more demand for irrigation water.

***Irrigation Water Use in Botswana*** Estimated irrigation water demand for the portion of the Aquifer Area in Botswana is 26 million $m^3$/a. In Botswana, a total irrigated area of 1,500 ha in the Tuli Karoo Aquifer Area was used to estimate the irrigated water demand based on the 17,320 $m^3$/ha/a water demand (Botswana, Central Statistics Office, 2007; Masamba, 2009). Generally, reclaimed wastewater offers an excellent source of water for irrigation in Botswana, but only 10 percent of the return flows from wastewater treatment plants are reused, the rest being lost to seepage and evaporation. In the Tuli Karoo Aquifer Area, there is nonetheless only one wastewater treatment plant from which water is put to productive use: in Bobonong, Botswana, the effluent is discharged to a eucalyptus plantation. Urban areas in the Tuli Karoo System with potential for wastewater use for irrigation include Selebi-Phikwe, Serowe and Tonota (Department of Agriculture and Agro-industry, 2011).

There are four farming systems in the irrigation sector in Botswana (Botswana, Central Statistics Office, 2007):

- Private irrigated farms owned by individuals and ranging in size from 1 to 100 ha (with the smaller farms being more common). These farms mostly grow high-value food crops for the local markets;
- Group schemes developed by government and donor agencies to provide livelihood alternatives to local people. These consist of 10 ha schemes divided into individual plots.
- Institutional schemes owned and operated by government organisations.
- Company-owned schemes owned and operated by companies such as the Botswana Development Corporation, which has 570 ha in the Tuli Karoo Aquifer area in Botswana, Mogobane and Kasane outside the aquifer area. This includes the Tuli Block, an area located at the confluence of the Shashe and Limpopo rivers.

***Irrigation Water Use in South Africa*** Estimated irrigation water demand for portion of the Tuli Karoo Aquifer Area in South Africa is 63.3 million $m^3$/a. The Water use Authorization and Registration Management System (WARMS)[2] database (2019) – containing information on registered water users in the aquifer area – was used to identify and estimate registered irrigation volume in the aquifer area.

[2] Water use Authorization & Registration Management System (WARMS), is the national register of water use for South Africa defined in terms of section 139 (2) (d) of the National Water Act 1998, to store & produce accurate water use information.

Notably, this volume may be over or under estimation of irrigation water demand as the process of validation and verification is on-going by the Department of Water and Sanitation, South Africa. Furthermore, there could be informal water use and irrigation not captured, which falls under General Authorisation permit. The types of farmers in the South African portion of the aquifer are smallholder and big commercial farmers (Council for Scientific and Industrial Research-Environmentek, 2003). Smallholder farmers focus solely on crop production, while commercial farmers are involved in crop, livestock and game farming and game reserves (Council for Scientific and Industrial Research-Environmentek, 2003).

***Irrigation Water Use in Zimbabwe*** Estimated irrigation water demand for the aquifer portion in Zimbabwe is 57.3 million $m^3/a$. The area proportion method was used to estimate the irrigation water demand based on the total irrigation demand for Mzingwane Catchment (63,000 $km^2$) of 514 million $m^3/a$, where portion of the aquifer (7,027$km^2$) lies. In Zimbabwe, sources of irrigation water include sand abstraction systems (water is pumped from rivers through well points sunk into riverbed sand) and dam-fed schemes, such as the Zhovhe Dam (Figure 2 and Figure 3). Smallholder farm plots vary in size from 0.1 to 0.5 ha/household (Government of Zimbabwe, 2019). Zhovhe Dam supplies both smallholder and commercial farmers with irrigation water, but most farmers far from the Limpopo and its tributaries, rely on groundwater. The advantage of having the Zhovhe Dam is its location at a high elevation enables irrigation water supply through gravity. Most smallholder farmers use inefficient surface irrigation methods (e.g., furrow and border systems), indicating great potential to increase water use efficiency by converting to drip systems and using soil and nutrient management tools. The farming systems in Zimbabwe include smallholder (communal), old resettlement, small-scale commercial, Agricultural and Rural Development Authority (ARDA) estates, A1 and A2 resettlement farming areas.

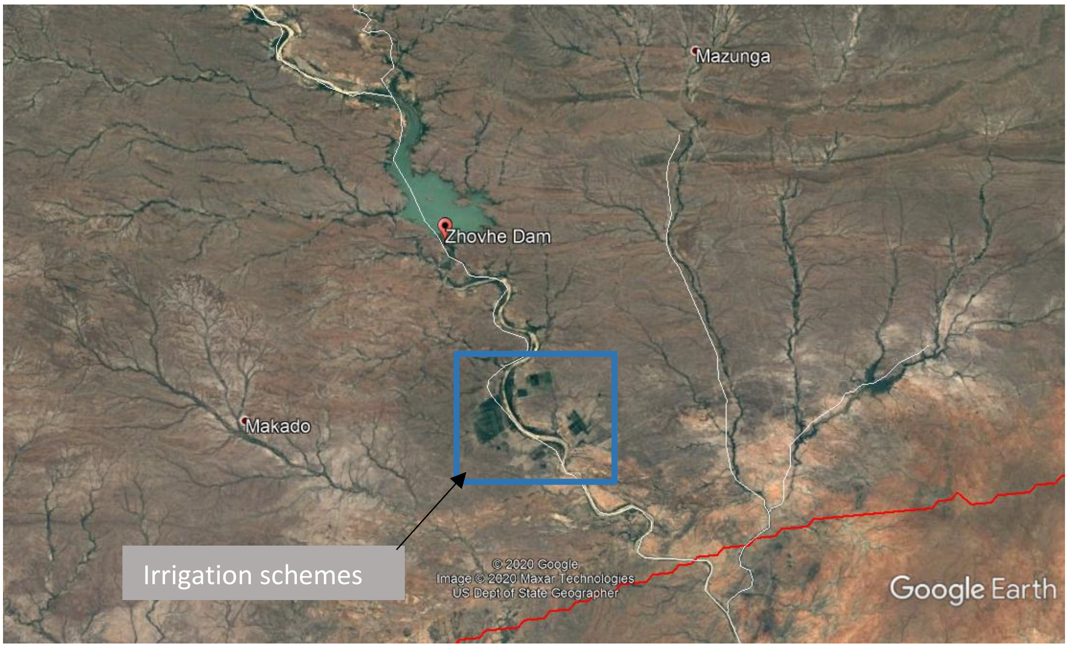


**Figure 2**. Location of Zhovhe dam and downstream irrigation sites, Ndambe 2 and Ndambe 1 (Google Earth, 2020).

## 2.3. Site Selection

***Visits to seven irrigation sites in the Tuli Karoo*** In order to identify the sites for the ag-water solutions component of the project, information was first collected from representatives from the Department of Crop production and Selebi-Phikwe Economic Diversification Unit (SPEDU) based in Selebi-Phikwe, in Botswana. Input was also sought from professionals at Department of Agritex and Rural District Council in Beitbridge, South Africa. Following review of collected information, examination of land use maps and discussion with authorities from three countries, visits were made to seven sites between 25 and 29 November 2019 (Figure 3). Three sites were in Botswana, and four sites were in Zimbabwe (Figure 3).

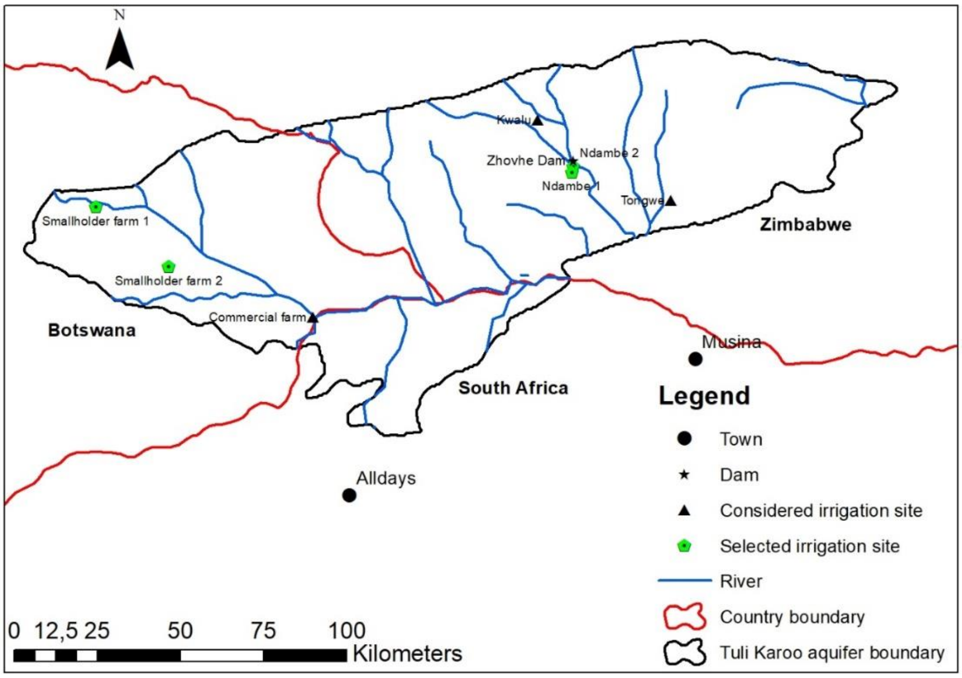


**Figure 3.** Irrigation sites visited in Tuli Karoo Aquifer Area

***Site Visits in Botswana*** Following a meeting at the Selebi-Phikwe Economic Diversification Unit (SPEDU) office in Selebi-Phikwe to decide on the farmers to be visited for the initial selection, it was decided to visit two smallholder farmers and one commercial farmer in Botswana. Three farms were visited (Table 3):

1. Smallholder farm 1 was first visited (Figure 3). This is an individual farm of 4 hectares and one shallow well, which employs six causal labourers (temporary workers). Water shortage was reported, and a shallow well used is 2.5m deep and is located on the river bank of Motloutse River. Hence, during the dry season the baseflow decreases, as the river dries up. The current (2019) crop of cabbage and green pepper did not do well due to water shortage. In early January 2020, the farmer will plant cabbage, tomato and green pepper.
2. Smallholder farm 2 was visited second (Figure 3). This is an individual farm of 6 hectares and two boreholes. They apply water every day, except when it is raining, due to the very hot weather conditions. Water shortage was reported, especially from August to December of every year. The two boreholes all 200m deep, and partially penetrated the sandstone formation. Water strikes are at 30m, 120m and 150m. The farmer tried to drill another borehole in 2019, but the final depth of this borehole only 80m. The water storage tank at the farm used for irrigation is 60,000 litres. They have 10 permanent workers; 6 from Botswana and 4 from Zimbabwe. The current (2019) crop of cabbage did not do well due to water shortage and diseases. Next year (2020) they will focus on tomato and green pepper crops, but this will need more labourers.

3. The commercial farm was visited last (Figure 3). This was a large commercial farm. The farm provided a good test site for an alluvial groundwater -based irrigation scheme. An estimate of 180ha of maize was going to be planted on the 1st of February 2020 and 1st of March 2020 and 250ha of bean crop distributed across different centre pivots was to be planted end of February 2020. For crop monitoring of pests and diseases, and water stress, the farmer reported that Stanbic Bank sends him a satellite image taken at 8m above the maize crop every second day. The based on the interpretation of satellite image the bank will advise the farmer accordingly if there is stress or diseases on the crops.

***Site Visits in Zimbabwe*** A meeting at the Beitbridge Rural District Council revealed that irrigation schemes in drought prone southern part of the country were rehabilitated and modernised to boost climate change adaptation methods and enhance agricultural productivity and resilience among smallholder farmers. The funding for these rehabilitations were facilitated in 2017 under the three year Zimbabwe Resilience Programme (US$5.3 million) funded by the United Nations Development Programme (UNDP) and implemented by a non-governmental organisation, CESVI (Italian, "Cooperazione e sviluppo", Cooperation and development). The overall project objective was to make the communities, local authorities, private partners and extension services be aware of the importance of working together in sustaining these irrigation schemes, to reduce water use and operational costs. CESVI collaborated with agriculture extension services to teach farmers on the importance of using business models to manage their irrigation projects so that they can set money aside for equipment and infrastructure rehabilitation and operation and maintenance. The NGO also helped smallholder farmers to move from flood irrigation to other technologies such as centre pivots, pressurised watering systems and drip irrigation and from low value crops to high value crops like citrus and sugar bean seed production. Ultimately, four irrigation (Kwalu, Ndambe 1, Ndambe 2 and Tongwe) schemes were visited (Table 3):

1. **Kwalu irrigation scheme** Kwalu Irrigation scheme was established in 1965 and has a total active area of 95ha. The scheme pumps water from the Umzingwane River using boreholes located at the edge of the river banks. The scheme has never had full irrigation of the irrigable 120 ha, even when it was first constructed. The major problem was the pumping capacity that cannot deliver adequate water to meet the total area crop requirements. Each farmer 0.2 ha (0.1 ha in 2 blocks). Pivot 1 has 35 ha, Pivot 2 has 26 ha and Pivot 3 has 34 ha. The canals were rehabilitated in 2011. There are 150 farmers in total, but only 95 farmers are active. The source of water is groundwater abstraction systems that use 4m-deep boreholes at the edge of the river bank to pump water from the river bed to the field. Crops grown include maize and sugar beans. Maize is grown throughout the year but sugar beans they plant it in February. The market areas for the green mealies include Beitbridge and Makhado along the Beitbridge road.
2. **Ndambe 1 Irrigation Scheme** The scheme has a drip irrigation system. The irrigation scheme area is 9 ha. Each family has three plots of 0.04ha each, to make a total of 0.12ha. There is no possibility of expanding the irrigation area because of the rock and hilly area around this scheme. The scheme uses electricity energy. Crop production: The crops grown include maize, beans, butternut and watermelons. Nutrient application includes livestock manure and fertiliser. The irrigation committee consists of 2 women and 5 men. Originally, 30 families benefited from the scheme, but now only 24 families are benefiting from the irrigation as some dropped off from the scheme. The system in the field uses pressure tanks to supply water to the drip irrigation system. The farmers irrigate for 7 hours/day, normally from 8am to 3pm.

3. **Ndambe 2 irrigation scheme** It is a gravity –flood irrigation system. Each farmer has 0.4 ha which are divided into 0.2ha on either side of the main canal in the irrigation scheme. Each 0.2ha plot takes 30-35 minutes irrigation time. The farmers each pay $8 per month for water to the ZINWA. The water bill amounts to $304/month. However they said the water allocation can be obtained from ZINWA. The farmers start planting sugar beans early march of every year. The source of water is Zhovhe Dam with a capacity of 133 million cubic metres.
4. **Tongwe irrigation scheme** The scheme was established in 1963 and has a surface irrigation system of 27ha. The scheme has 75 farmers. Each farmer has 0.4 ha plot. This 0.4 ha takes 10 hours (either 6am-4pm or 6pm to 4am) to irrigate. Crop production: The maize crop is planted with fertiliser- D and top dressed with ammonium nitrate fertiliser at 2 and 4 weeks or when tasselling. They start planting beans around 15 February of each year. Tongwe River feeds into Mutetengwe River and Mutetengwe River feeds into Mzingwane River.

**Table 3.** Characteristics of irrigation sites visited during site selection

| Irrigation scheme | Country (Elevation - m) | Year started | Annual rainfall (mm) | Water source | Total Area (ha) | Number of farmers | Crops grown | Market |
|---|---|---|---|---|---|---|---|---|
| Commercial farm | Botswana (537) | 2016 | 450 | Boreholes | 400 | 1 | Maize, beans | Johannesburg |
| Kwalu | Zimbabwe (573.3) | 1965 | 400 | Borehole along the Mzingwane River bank | 95 | 150 | Maize, beans | Beitbridge; Makhado along the Beitbridge road |
| Smallholder farm 2 | Botswana (744) | 2010 | 400 | Boreholes | 6 | 1 | cabbage, tomato, green pepper | Local; Mr Veges and Choppies supermarket in Selebi-Phikwe |
| Smallholder farm 1 | Botswana (685) | 2010 | 400 | Shallow well (2.5m deep) | 4 | 1 | cabbage, tomato, green pepper | Local; Mr Veges and Choppies supermarket in Selebi-Phikwe |
| Ndambe 2 | Zimbabwe (536.7) | 2008 | 450 | Zhovhe Dam Capacity of 133 million $m^3$ | 18 | 38 | Maize, beans, citrus trees – oranges | Beitbridge; Makhado along the Beitbridge road |
| Ndambe 1 | Zimbabwe (535) | 2007 | 450 | Borehole along the Mzingwane River | 7 | 24 | Maize, beans | Beitbridge; Makhado along the Beitbridge road |
| Tongwe | Zimbabwe (510.8) | 1963 | 450 | Tongwe Dam | 27 | 75 | Maize, beans | Maize–locally; beans - SEDCO |

**Selecting irrigation sites** Five criteria were developed to help filter the longer list of seven sites visited, into a smaller set of sites on which water-saving technologies could be introduced (Table 4). The criteria were farm size, purpose for production, presence of smallholder and commercial farmers, baseline information of farms and accessibility of the sites.

**Table 4.** Selection criteria for trial sites

| Criteria | Logic |
| --- | --- |
| **Farm size** | Farms less than 2 hectare are of more interest because of their water abstraction rate. Also, the productivity of farms greater than 2 hectares may be higher. This includes crop yield per unit area of land and income from sales of produce per unit area of land. Farms of such sizes greater also have the advantage to access public subsidies/credit facilities. Therefore, they tend to have greater capacity for irrigation development. |
| **Water abstraction** | Water abstraction from both groundwater and surface water sources were considered, although use of groundwater from the sandstone or alluvial aquifers was preferred |
| **Irrigation method** | Gravity and pressurized irrigation methods were considered to understand the impacts of energy use on farm income. |
| **Purpose for production/cropping system** | Small to large scale commercial farmers are more likely to adapt improved agricultural water management improvements as economic gains are directly related to improved water use. Traditional backyard farmers are mainly for subsistence purposes and incentives might more challenging unless water scarcity or labor are constraining factors. |
| **Presence of Smallholder farmers** | Smallholder farmers contribute to food security at all levels (household, local and national), employment, poverty alleviation, and economic growth (Delgado, 1997; Deininger and Byerlee, 2011; Collier and Dercon, 2014; Samberg et al., 2016). It is therefore key that lessons be learned from engagement with smallholders. |
| **Baseline information on farms** | Farms with baseline information such as crop yields, agronomic practices (fertilizer application rates, weed/pest management), water use and cost of energy for production are important because they provide reference point against which WFD or chameleon-based management can be measured in addition to the control treatment established in this study. |
| **Accessibility of site** | The easy with which the site can be accessed is important, when the researcher carries out field work. This helps to plan for effective use of time during field visits. |

Note: Traditional backyard gardening = less than half a hectare, Emerging farmers = 1 – 1.5 hectares, Smallholder farmers = less than 2 hectares, Commercial farmers = 10 hectares and above

***Four Sites Selected*** Application of the selection criteria (Table 5) led to selection of four sites in the two countries. In Botswana, Smallholder farm 1, with boreholes next to a river, possessed an interesting mix of surface and groundwater use. Smallholder farm 2, by contract, looked to be a strong example of sandstone-groundwater-based irrigation scheme, and as such comprised a strong area of focus. In Zimbabwe, most sites satisfied key criteria. Nonetheless, Kwalu is fairly inaccessible and hence it was excluded. As the Tongwe scheme is based solely on surface water, and does not face water shortage, conjunctive water management and groundwater did not feature centrally. Ndambe 1 and 2 use alluvial-based boreholes and dam-water, respectively. The four sites (Table 5) thus selected were:

1. Smallholder Farm 1: draws from shallow alluvial groundwater from sand river, and used drip irrigation
2. Smallholder Farm 2: draws from groundwater sandstone layer of aquifer, used drip
3. Ndambe 1: draws from groundwater which results from surface flows, and used drip irrigation
4. Ndambe 2: draws from surface water, used flood

**Table 5.** Irrigation sites, classified according to selection criteria

| Irrigation scheme/selection criteria | Location | Irrigation system | Water source | Area (ha) | Ownership | Presence of baseline information | Accessibility | Comment |
|---|---|---|---|---|---|---|---|---|
| Commercial farm (Not selected) | Botswana | Sprinkler | Boreholes | >100 | Individual/ Company | Yes | Relatively difficult but no need of 4 X 4 vehicle; Far from Smallholder farmer 2 farm | Would be interesting to compare the sensors results with the satellite results captured every second day by Stanbic Bank |
| Smallholder farm 1 | Botswana | Drip | Shallow well (6 m deep) | 2-10 | Individual | Yes | Easy | Bobonong Department of Crop production has worked well with this farmer |
| Smallholder farm 2 (Selected) | Botswana | Drip | Boreholes | 2-10 | Individual | Yes | Easy | Owner keen to use the management tools |
| Ndambe 1 (Selected) | Zimbabwe | Drip | Borehole along the Mzingwane River | >10 | Communal | Yes | Easy; near the Zhovhe Dam; no need of 4 x 4 vehicle | Would be good to have drip system in both countries |
| Ndambe 2 (Selected) | Zimbabwe | Gravity flow - flood | Zhovhe Dam | >10 | Communal | Yes | Easy; near the Zhovhe Dam; no need of 4 x 4 vehicle | Close to Ndambe 1, hence easy accessibility |
| Tongwe (Not selected) | Zimbabwe | Gravity flow - flood | Tongwe Dam | >10 | Communal | Yes | Easy; near the Beitbridge road; no need of 4 x 4 vehicle | Uses water from dam and they reported that there is no water shortage |
| Kwalu (Not selected) | Zimbabwe | Gravity flow - flood | Borehole along the Mzingwane River bank | >10 | Communal | Yes | Relatively difficult; far from Ndambe1 and 2; no need of 4 x 4 vehicle but a normal bakkie | Uses 3 sand water abstraction schemes; the farmers seemed more organised |

Note: Highlighted rows show the final selected sites.

***Four additional findings from initial visits*** At least four findings were apparent from initial visits. First, a common challenge for all irrigation schemes selected was water shortage and the high temperatures stress crops even if irrigation is done twice a day. This suggests the need to introduce water saving technologies to improve agricultural productivity with the little available water resources. Second, there is a lack of irrigation scheduling. The farmers do not practice any irrigation scheduling, except for the commercial farmer to determine how much and when to irrigate their crops timeously. This presents an opportunity to introduce capacity building for agriculture water management technologies such as water and nutrient management tools as well as simple irrigation scheduling practices. Third, use of furrow and flood irrigation methods result in huge irrigation water and nutrient losses, despite water scarcity. Although the farmers would like to extend the available water resources by using more efficient systems, they fall short of raising the capital investment required to fund installation of improved systems such as drip system**.** Fourth, pests and diseases**.** The army worm was mentioned as one of the significant threat to maize production, especially in Zimbabwe as it had reduce the crop yield significantly. This threat is exacerbated by the fact that the arm worm has become resistant to the chemical that they use for spraying it.

**Box 1: Project implementation in the context of a pandemic**

Unfortunately, while four sites were selected for field activity at the end of 2019, initial plans were adapted in light of field restrictions associated with Covid-19. As roll-out began in the first quarter of 2020, the world was affected by COVID-19 pandemic. In southern Africa, this constrained the ability to travel to field sites and across countries. In the context of the project, while site visits were made in the first two months of 2020, the in-person support throughout the crop growing season that is normally provided was not possible. Such disruptions manifested themselves differently in Botswana vs. Zimbabwe. Unfortunately, the disruptions adversely affected Botswana's use of the water management tools and viable results were not produced. In Zimbabwe, however, farmer dedication and communication resulted in effective use of the tools. Persistent virtual support through telephonic calls, text messages and WhatsApp platforms were essential to this effort.

## 2.4. Agricultural production and markets on Ndambe 1 and 2 irrigation schemes

***Favourable local and export markets are important for stimulating irrigated agriculture in rural communities***. Readily accessible and functional markets (road network, agro-processing,) are very important to stimulate investment under irrigated farming (Singh et al., 2016). The irrigated produce is marketed to the local market including surrounding boarding schools, retail supermarkets and other institutions. Agro-dealers are encouraged to pay competitively for farm products, particularly vegetables and cattle, which are the mainstay of the aquifer area.

***Agricultural production and markets on Ndambe 1 and 2*** Given the adaptation to focus on Zimbabwean schemes in light of Covid-19 restrictions (see Box 1), focus here is placed on baseline conditions in Ndambe 1 and 2. Zhovhe Estate (an agricultural land near the Zhovhe Dam owned by several investors) aims to produce for the local and export markets. This helps to create jobs for the community and enhance food security for more people. The production system for different crops in Ndambe 1 and 2 irrigation schemes are presented in Tables 6 and 7. The farmers are contracted by a seed company to produce sugar beans.

**Table 6.** Maize production in Ndambe 1 Irrigation Scheme, Zimbabwe

| **Activity/input** | **Labour/ input quantity** | **Hours per hectare** | **Mandays per hectare field** |
|---|---|---|---|
| Ploughing | Animal drawn plough; 4 donkey-team | 8.70 | 1.10 |
| Planting | Hand planting from a tin of seeds<br>5 workers<br>Seed: 25kg/ha | 6.97 | 4.40 |
| Fertilizing | Hand planting from a tin<br>5 workers<br>Compound D: 150kg/ha<br>Ammonium Nitrate: 150kg/ha | 1.90 | 1.20 |
| Weeding | Hand hoe<br>5 workers | 14.00 | 8.80 |
| Pest and disease control and spraying | 5 x Knapsacks | 4.27 | 0.53 |
| Harvesting | Hand<br>5 workers | 5.00 | 3.12 |
| Shelling | Hand<br>5 workers | 8.32 | 5.20 |
| Winnowing and grading | Hand<br>5 workers | 1.18 | 0.74 |
| Bagging and storage | Hand<br>5 workers | 2.54 | 1.60 |

Maize stalks are used for feeding livestock. 8 hours is equal to 1 manday; Irrigation cycles per season were 13-14; Total yield for 9 ha was 25.2 tonnes and 0.3 tonnes was for self-consumption

**Table 7.** Bean production in Ndambe 2 Irrigation Scheme, Zimbabwe

| **Activity/input** | **Labour/ input quantity** | **Hours per hectare** | **Man-days per hectare field** |
|---|---|---|---|
| Ploughing | Animal drawn plough; 4 donkey-team | 8.70 | 1.10 |
| Planting | Hand planting from a tin of seeds<br>5 workers<br>Seed: 100kg/ha | 9.70 | 3.60 |
| Harrowing after planting | 1 x farmer<br>Two-ox team | 1.90 | 0.24 |
| Fertilizing | Hand planting from a tin<br>5 workers<br>Compound D: 200kg/ha<br>Ammonium Nitrate: 100kg/ha | 1.00 | 0.63 |
| Weeding | Hand hoe<br>5 workers | | 40.00 |
| Pest and disease control and spraying | 5 x Knapsacks | 4.27 | 0.53 |

| Activity/input | Labour/ input quantity | Hours per hectare | Man-days per hectare field |
|---|---|---|---|
| Harvesting | Hand<br>5 workers | 17.06 | 2.14 |
| Threshing, winnowing and bagging | Hand<br>5 workers | 42.60 | 5.33 |
| Grading | Hand | | 2.00 |

Stover is used for feeding livestock. 8 hours is equal to 1 manday; Irrigation cycles per season were 11; Total yield for 18 ha was 45 tonnes and 0.5 tonnes was for self-consumption

The variation in crop yield from the irrigation scheme is presented in Figure 4. The low maize crop yield in 2018 was due to infestation of the armyworm, while the low yield for bean and wheat crops was low in 2015 due to poor seed and shortage of other inputs.

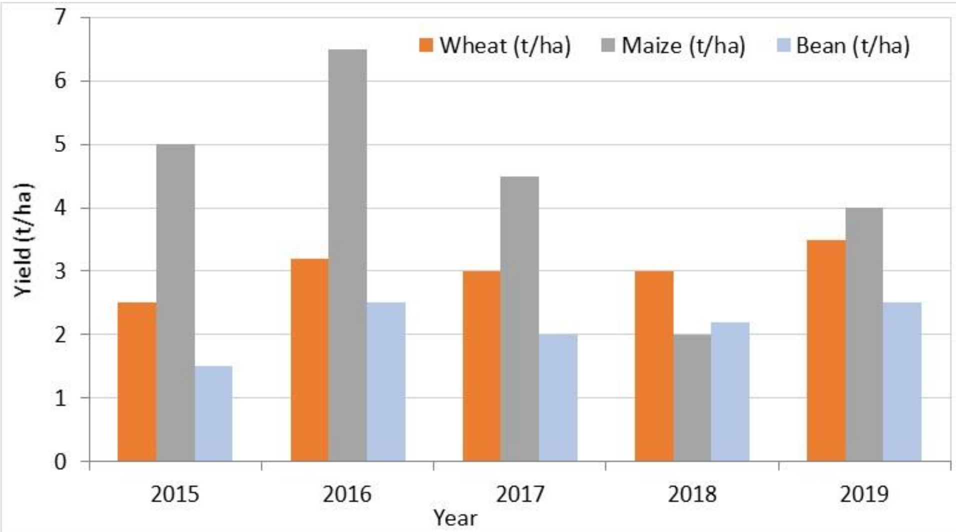


**Figure 4.** Crop yield variation over the years for Ndambe 2 Irrigation Scheme, Zimbabwe

The vegetable yield variation from an irrigation scheme (smallholder farmer 2 in Figure 3) in Molalatau area, near Bobonong area in Botswana is presented in Figure 5. The low crop yield in 2019 was due to flooding of the crops in parts of the field. The farmer has drilled one more borehole about 120m deep and reaching the sandstone formation to increase water availability for irrigation. However, the borehole depth did not pass through the sandstone formation. Besides the water resource availability from additional borehole drilled the farmer also indicated the there is need to improve the field water supply and distribution by repairing/ mending the leaking drip kits and maybe replacing the extensively leaking drip kits to ensure all the crops receive enough water for maximum production. Most (> 90%) of the produce is sold to local communities and local super markets such as Choppies, and less than 9% of the yield is discarded or feed to livestock and only about 1% is for self-consumption.

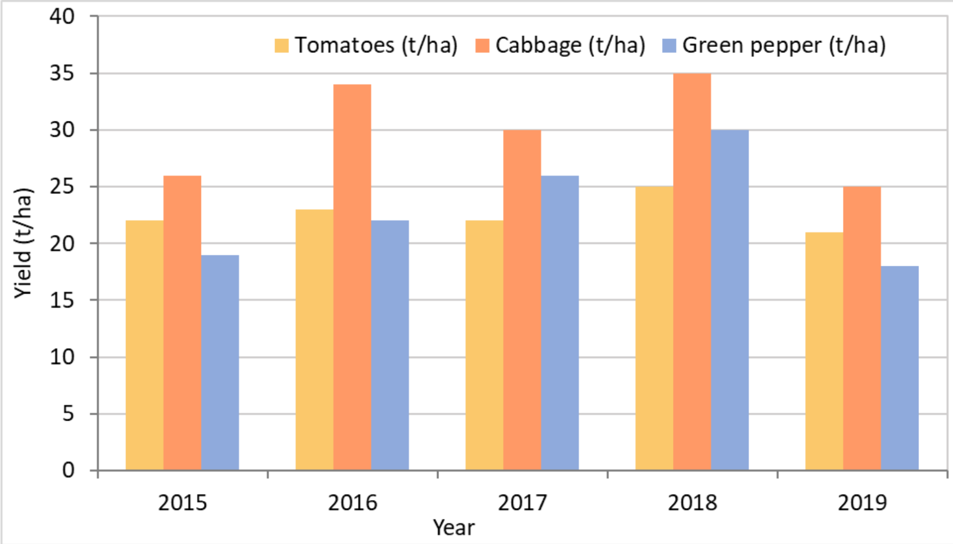


**Figure 5.** Crop yield variation over the years for Smallholder farmer 2 in Molalatau area, Botswana

# 3. Methodology

## 3.1. Methodological framework

***Experimental and control plots*** A comparison of experimental vs control field plots was used to assess the impact of soil-water and nutrient monitoring tools, especially for Ndambe 1, Ndambe 2, Smallholder farmer 1 sites. The replicated control design, where each experimental treatment was near a control treatment, was used. For Ndambe 1 and 2 irrigation sites, different farm plots owned by different farmers, but with same crop and management practices were selected to represent the experimental and control plots, while for Smallholder farmer 1 farms, different fields within the same farm were selected to represent experimental and control plots. A control was taken as farmer common management practice of soil-water and nutrient applications, i.e., where monitoring technologies were not introduced. Farmers with a plot adjacent to the plot where the tools were used was taken as control and instructed them not to apply the knowledge newly gained in the control plot, but to continue managing the crop as usual. Experimental treatment was taken to be a field where farmer soil-water and nutrient applications were informed by soil-water and nutrient monitoring technologies.

***Controls were either current or historic, depending on data availability*** Current controls are monitored simultaneous with the experimental treatment, whereas historic controls are obtained from historic records (Kramer and Font, 2017). Using current control approach such as in Ndambe 1 and Ndambe 2 sites assumes that conditions such as soil type and fertility and crop management are the same for each pair of control and experiment treatments in the same farm. In farms where it was impossible to have concurrent control and experimental treatments, past data from previous crop season and same crop phenotype was used for comparison against the new experimental treatment data. This design approach is referred to as before-and-after design (Kramer and Font, 2017).

***Assessment of farmer learning impacts on experimental vs. control plots considered crop yield and water productivity*** The impacts were assessed using the "difference in difference" method at the farmer and irrigation scheme scales, where the changes in selected indicators (e.g., crop yield and water productivity) among the experimental fields of the project are compared to changes among the control fields (Hayashi et al., 2011). Impact at plot and scheme levels was inferred if the changes among the experimental treatment fields are more favourable than changes among the control fields. This analysis also considered random variables that might affect this comparison, such as soil type and plant population, which might vary in the same irrigation scheme such as Ndambe 2, which has sandy clay and sandy soils.

## 3.2. Plot selection

Within the irrigation schemes, plots with similar soil types were selected for experimental and control treatments for different crops to reduce bias. To account for natural field variability within a selected farm, experimental plots (0.2-0.5 ha) were selected for monitoring. Ndambe 1: Out of the 18 farmers in the whole irrigation scheme, four female and four male farmers were selected to participate in this study. Ndambe 2: Out of the 38 farmers in the whole irrigation scheme, four female and four male farmers were selected to participate in this study. For both Ndambe 1 and 2, eight sugar beans plots were randomly selected from each irrigation scheme and monitored. Four farmers were selected to represent the control and the other 4 represented the experiment for each irrigation scheme. A summary of the selected sites and water sources is shown in Table 8.

**Table 6**. Summary of selected sites, control types and water sources in the study area

| Scheme | Plot | Experimental treatment (ha) | Concurrent control (ha) | Historic control | Crop |
|---|---|---|---|---|---|
| **Ndambe 1** | 1 | 0.20 | 0.20 | 0.2 | Sugar beans |
| | 2 | 0.20 | 0.20 | | Sugar beans |
| | 3 | 0.20 | 0.20 | | Sugar beans |
| | 4 | 0.20 | 0.20 | | Sugar beans |
| **Ndambe 2** | 1 | 0.20 | 0.20 | 0.2 | Sugar beans |
| | 2 | 0.20 | 0.20 | | Sugar beans |
| | 3 | 0.20 | 0.20 | | Sugar beans |
| | 4 | 0.20 | 0.20 | | Sugar beans |
| Total | **12** | **2.4** | **2. 0** | **0.4** | Sugar beans |

## 3.3. Data collection and monitoring timeline

Monitoring involved the regular observation and recording of soil-water, irrigation water use, frequency of irrigation, nutrient loss and crop yields from both control and experimental plots over the project duration. The mechanical WFD, nitrate testing strips, electrical conductivity and chameleon sensors and readers were used in data collection. As a first option, one can use the wetting front detector alone for just water management. A second option involves use of the WFD with nitrate strips to manage water and nutrients leaching. In this study we used a combination of WFD and nitrate strips for testing nitrate leached. The farmers also used the chameleon sensors with chameleon reader. Since the chameleon reader was shared by all farmers in the same irrigation scheme, its cost was divided by the number of farmers using the reader for assessment of production costs. In this study a WFD and nitrate strips, chameleon sensors and chameleon reader were used in each farmer plot of 0.2 ha.

The mechanical WFDs were installed at 0.3m depth to collect the soil-water drainage used to test nutrient loss. The WFD was only for monitoring root zone leaching of nutrients, while the chameleons were used to visualize soil moisture patterns. Each chameleon tool had three sensors, which were installed at 0.2m, 0.4m and 0.6m depths to record soil-water at these different depths, depending on the crop root-zone depth. The instruments installed in each plot were a WFD and chameleon sensor (Table 8). For the large field (13 ha) three WFDs and three sensors were installed across the diameter of the field. Each scheme or farm had a reader to read, store and upload data through wifi from the sensors for sharing. A box of nitrate strips for 100 nitrate tests using the colorimetric method was also required for each scheme. The monitoring period covered two crop growing seasons and started from 3 February and ended on 30 September, 2020.

*Farmer training* Farmer training was important to allow farmers to maintain the tools in both experimental and control plots. Farmers were trained on the installation and use of monitoring equipment of WFD and chameleon water sensors including setting up sensor reader to wifi for uploading and sharing of data. The farmers uploaded the collected data from the sensor reader to the VIA website. The higher the frequency of data collection, the better the data trend. With the facilitation of the researcher, the data trend observed was shared and discussed with the farmers to understand what transpired in the field and identify corrective measures in terms of soil-water and nutrient management. From the discussion, corrective measures were identified and implemented by the farmer in next days or in a following crop season.

## 3.4. Indicator selection and population

This study evaluated impact of farmer learning from using water, nutrient and salt monitoring tools on irrigation decision making to influence yield, soil nutrient loss (environment), and net income (economy) in irrigated agriculture. Indicators that were selected to determine whether impact was achieved or not were water use and frequency of irrigation, nutrient loss beyond root zone, soil salinity levels, labour, crop yield, gross irrigated water productivity and crop production income. Water use was the key indicator as the aim was to reduce and effectively use scarce water resources in the study area. A brief description of how the indicators were measured and sources of information are presented in Table 9.

**Table 7**. Indicators and data sources

| Indicator | Calculation | Data source |
|---|---|---|
| **Water use** | Amount of water supplied to the field to fill the soil to capacity depends on the available soil-water moisture. Total water use is calculated by multiplying the total water supplied per unit time from furrow canal or number of drips in a plot by the total irrigation time and summing up all irrigation events from day of planting to day of harvest (growing season). It is important to look at water application for each irrigation event over time through different cropping stages, the impact of water and nutrient on yield happens at crucial parts of the cropping stage. | Soil-water is measured by the chameleon sensor, interpreted by farmers, uploaded to website for viewing by IWMI staff. |
| **Frequency of irrigation** | Summation of the total or irrigated days per week and growing season. The chameleon sensor installed in the plot indicates amount of soil-water and then the farmer can irrigate or not based on this information. | Farmer records of dates when irrigation was done in the plots. |
| **Nutrient loss** | Cumulative nitrate loss per growing season is compared from experimental and control plots. The nitrate loss is assessed by comparing the colour change from the nitrate strips with the value ranges on the nitrate strip chart for each test. | Nitrate strip readings, applied and interpreted by farmers. |

| Indicator | Calculation | Data source |
|---|---|---|
| **Soil salinity** | Grams of salt per kg of soil. It measures the cumulative soil salts dissolved in drainage water per growing season. | Measurements of electrical conductivity from soil-water drainage beyond the root zone using electrical conductivity meter |
| **Labour** | Summation of the total hours of work done in the plot per growing season. The hours are converted to cost by using the labour cost per hour. | Farmer interviews were done to assess the numbers of hours |
| **Crop yield** | Weighing the total mass in kilogrammes (kg) of crop yield harvested per growing season. | Records of mass of harvested crop |
| **Irrigated water productivity** | Dividing the crop yield by the total water applied in a plot per growing season. | Farmer records of yield and irrigation water applied |
| **Crop production income** | Subtracting the total expenses from the total sales from the harvest per growing season (cost-benefit analyses) | Records of expenses and crop sales per plot |

### 3.4.1. Water use and frequency of irrigation

Different methods were used for estimating water supplied to the fields from irrigation canal vs. boreholes. The discharge from canals was estimated by taking several measurements of velocity of flow using the time of travel of a float (an orange peel) between two points in the canal and multiplying the average velocity by the area of water flow in the canal (Weight and Sonderegger, 2001). Several velocity readings were made and an average was used in the estimation of the canal water discharge to the field. These measurements were taken at the start and end of the season as the flow in the canal did not vary at each irrigation event. The canal is supplied from Zhovhe Dam, less than a kilometre from the irrigation scheme. The total irrigation water applied during the growing season, was calculated by multiplying the canal discharge by the number of irrigation events per season, multiplied by the duration of the irrigation events recorded by the farmers.

Irrigation water discharge from boreholes was estimated by taking several measurements of time taken to fill a 20-litre bucket from the borehole mainline. An average time to fill the bucket was then used to estimate the discharge. For the drip irrigation systems, the average irrigation water discharge into the field was estimated by collecting discharge from four drip nozzles in each plot over the irrigation period. There were no water discharge losses due to drip line leakages except through the drip nozzles. We checked drip uniformity by selecting four drip nozzles covering 20%, 50% and 80% of the field length. An average discharge volume per drip nozzle was then multiplied by the total number of nozzles and time of irrigation of the plot to estimate the total irrigation volume supplied to the field per irrigation event.

The frequency of irrigation for all monitored plots in the schemes was calculated by counting the number of irrigation times from planting to harvest. Under the experimental plot, water management practice (i.e., when to irrigate) was informed by the results from the installed chameleon sensor. The chameleon sensors were installed at 0.2 m, 0.4 m and 0.6 m depth below the ground surface at the last third length of the field edge of a furrow for furrow irrigation and below a drip nozzle for drip irrigation. A chameleon reader was used to take readings from the sensor. The reader has three indicator buttons corresponding to the three depths the sensors are installed. Indictor colours of blue, green and red indicate very wet soil, moist soil and plant can easily extract water and dry soil and plant has difficulty in extracting water from soil matrix, respectively. Based on this colour coding the farmer can decide whether to irrigate and whether sufficient irrigation water has been applied. If all the lights at three depths are blue, it indicates over-irrigating and soil-water is above the field capacity. However, whether we are over-irrigating or not depends on a combination of factors such as root depth, amount of water applied and the soil water holding capacity. Detailed description of the chameleon sensor and connection to the reader is presented in Schmitter et al. (2020).

One chameleon sensor was installed in each plot on the last quarter length of the plot due to the small area (0.2 ha) of the monitored plots. The total water supplied to the field is related to the frequency of irrigation. The higher the irrigation frequency, the higher the water supplied to the irrigated field.

#### 3.4.2. Nutrient loss beyond root zone

A major source of crop nutrients required for crop growth is soil. The nutrient loss beyond the crop root zone from control and experimental plots was assessed by collecting soil-water drainage from a WFD tool installed at 0.3m below the soil surface based on the crop root-zone depth. The WFD was installed directly below a drip nozzle to ensure the drainage from the nozzle is captured. WFD funnel captures drainage from the soil root-zone. The root depth for beans and most vegetables including pepper varies from 0.45-0.60 m (DAFF, 2010). One WFD was installed in each plot and normally it is installed at two-thirds of the effective root depth (Schmitter et al., 2020). Nitrate strips were then dipped into the soil-water drainage and the changes in intensity of purple colour of nitrate strip showed the level of nitrate loss beyond the root zone. High nitrate levels are shown by purple test strips, while lower nitrate levels are shown by pink or white test strips. Under the experimental plot, the decision on nutrient and water applications was informed by the results from soil-water drainage and nitrate loss levels. For example, if the nitrate loss is high, no nutrients will be further applied and no over-irrigation is allowed.

#### 3.4.3. Labour

Labour (family or hired) is an important and costly farm input from land preparation to harvesting that needs to be efficiently used. The labour cost was calculated from the number of hours and persons required to complete farm tasks and local labour cost per hour for each irrigation scheme. The farm tasks included ploughing, seeding or planting, watering, fertiliser application, weeding, spraying of pesticide and harvesting per monitored plot. Hence, this exercise relied on farmer records and observations in the field.

#### 3.4.4. Crop yields

Crop yield is the crop harvested per area of land and is usually reported in kilograms/hectare (kg/ha). Crop yield was measured by weighing the total harvest per plot area (0.2 ha) for each farmer from the two irrigation schemes. The yield of dry beans was packed in 50 kg sacks, and the number of sacks was recorded in the field books. The mass of a 50 kg sack was weighed and then extrapolated to dry bean yield per ha. Farmers' incomes are based upon the amount of yield they produce. Therefore, a farmer is always balancing the price of growing crops with the expected yield so he or she makes profit.

#### 3.4.5. Irrigation water productivity

The water productivity is a performance indicator used to describe the relationship between water applied and agricultural product output (Annandale et al., 2011). It is a measure of the efficiency of on-farm water use. It can be assessed from three broad perspectives, i) physical water productivity (crop output per unit of total water consumed (i.e. actual evapotranspiration), ii) water productivity (crop output per unit of irrigation water applied by farmers) and iii) economic water productivity (value of crop output produced per unit of total water consumed or applied (Sharma et al., 2018). In this study, water productivity was calculated by dividing dry bean yield by the gross volume of irrigation water (gross water use) during the growing season the gross irrigation water productivity for farmers growing the same crop was assessed from records of gross irrigation water amounts applied not water consumption, and crop yield from each plot. There was no rainfall received during the growing period.

### 3.4.6. Crop production income

Crop production income refers to profits and losses incurred through operating a farm or irrigation scheme. The crop production income was obtained by comparing the total farming expenses against total sales (cost-benefit analyses) for each monitored plot and an average was used for the plots under farmers practice and plots were management tools were used. The higher the income the more profitable the irrigated agriculture businesses.

### 3.4.7. Farmers' experience on using the management tools

After harvest, the farmers (n=12) that used the management tools were asked about what they learnt when using the management tools, whether they would like to continue using the tools, was the support and use of tools adequate for their needs and what support they would want from the researchers going forward. The responses to these questions were presented as a summary.

### 3.4.8. Assessment of significance of differences.

After determining crop yields, nutrient loss and other indicators from control (farmers practice) and experimental (use of management tools) treatment, the data were analysed for significance of difference using the paired *t*-test at 0.05 (5%), p value. The *t*- test allows comparison of the average values of two data sets, and determine if they came from the same population or not (Kramer and Font, 2017). The outcome of the *t*- test produces a *t*-value which is compared with value obtained from a critical value table (known as the *t*-distribution table). When the calculated *t*-value is greater than the table value at a certain significance level, the null hypothesis that there is no difference between means can be rejected. Further, when calculated p is less than 0.05 then the result is significant at $p < 0.05$. The significance of these results was also presented and discussed in the context of the COVID-19 pandemic.

# 4. Results

The results presented here are for bean crop from two irrigation schemes in Zimbabwe, one using flood irrigation method and the other one using drip irrigation. As noted above, the results from sites in Botswana where incomplete due to suspension of field work in response to COVID-19 pandemic and are not presented here.

## 4.1. Water use and frequency of irrigation

The farmers that used the chameleon and WFD tools (experimental) reduced the number of irrigation cycles compared to the farmers that did not use the tools (control) in both irrigation schemes (Ndambe 1 and Ndambe 2). The irrigation frequency for bean crop per season decreased from 11 to 9 cycles for flood irrigation method, while for drip irrigation it decreased from 11 to 10 cycles per season. The total irrigation volumes for a field size of 0.2 ha, for flood irrigation method were 2,597 $m^3season^{-1}$ (farmer practice) and 2,125 $m^3season^{-1}$ (using management tools), while the volumes for drip irrigation method were 915 $m^3season^{-1}$ (farmer practice) and 832 $m^3season^{-1}$ (using management tools). The total seasonal volume of water applied per hectare is shown in Figure 7. This reduced the amount of irrigation water used, and saved time and labour, for both irrigation methods.

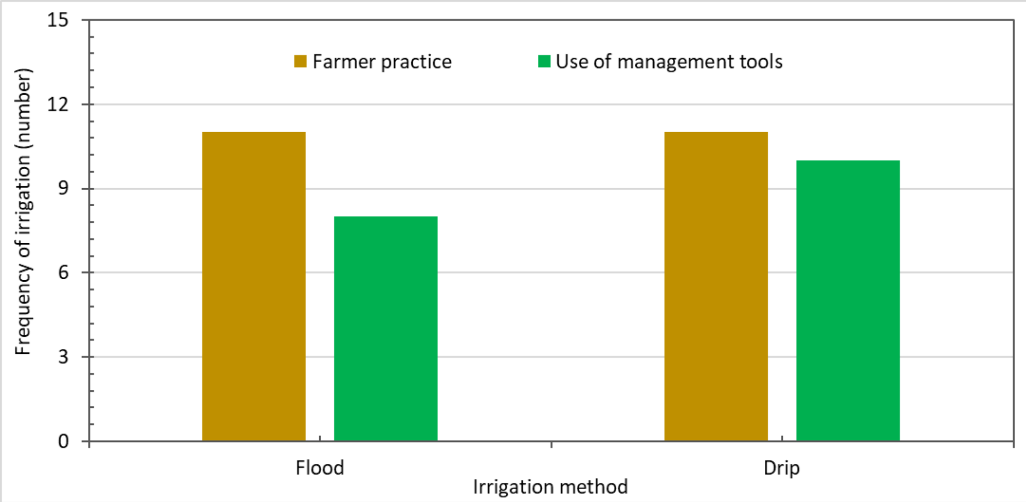


**Figure 6.** Water use and frequency of irrigation

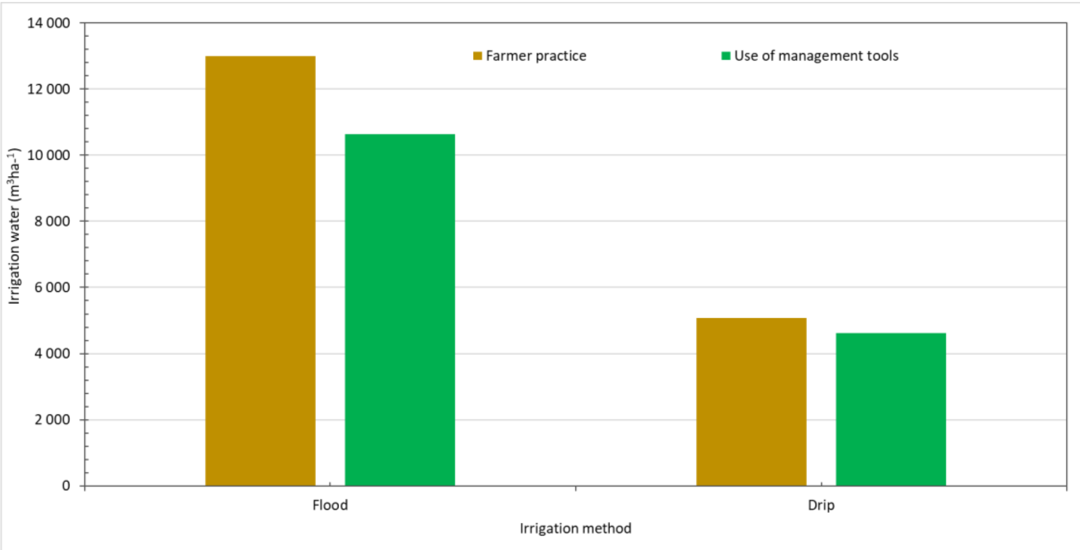


**Figure 7.** Irrigation water applied per hectare per season

## 4.2. Nutrient loss beyond root zone

The seasonal average nutrient loss at 0.3m below the ground surface (Figure 8) was higher under farmer practice (153 $mgL^{-1}$) compared to farmers that used the management plots (121 $mgL^{-1}$). This indicates that use of management tools can result in reduced nutrient loss beyond the crop root zone by 21% and result in increased water use efficiency by the crop for increased crop yield.

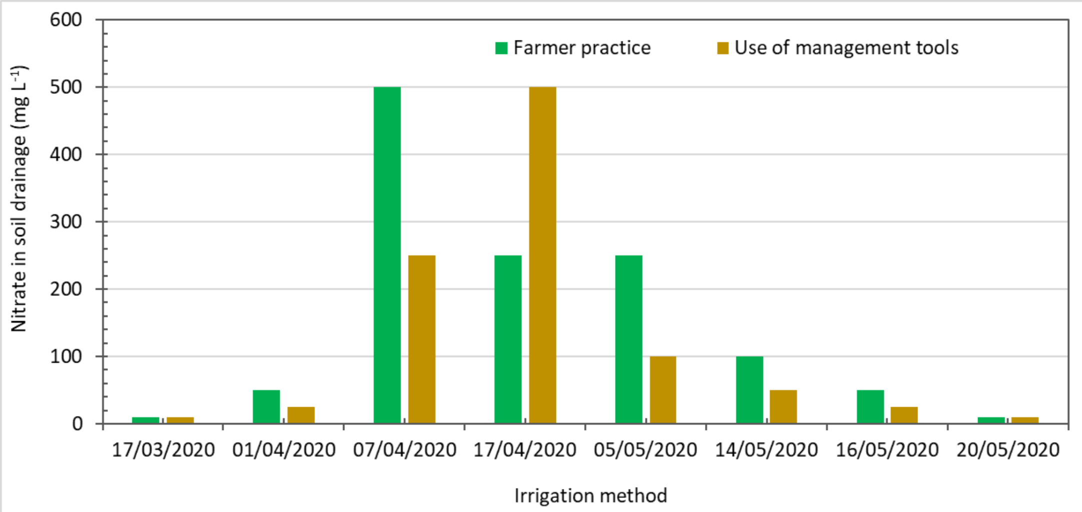


**Figure 8.** Nutrient loss beyond the root zone for flood irrigation

### 4.3. Labour

The reduced frequency of irrigation and weeding resulted in seasonal labour savings of 27% (on these two inputs) for farmers that used management tools compared to farmers that did not use the tools (farmer practice). The seasonal irrigation frequency reduced from 11 to 9 under use of management tools, while the weeding frequency reduced from 4 to 3.

### 4.4. Crop yields

Use of management tools increased crop yields under both flood and drip irrigation methods, indicating improved irrigation water use efficiency (Figure 9). Crop productivity under farmer practice was 2,000 kgha$^{-1}$ and 1,250 kgha$^{-1}$ for flood and drip irrigation, respectively. This crop grain yield increased to 2,250 kgha$^{-1}$ and 1,806 kgha$^{-1}$ under use of management tools for flood and drip irrigation, respectively. The grain yield under drip irrigation was lower than that under flood due to delayed planting (planted in April instead of end of February) under drip method and frost that affected the crops during the growing season. The delay in planting was due to pump breakdown, which was fixed finally in April by an NGO in the area.

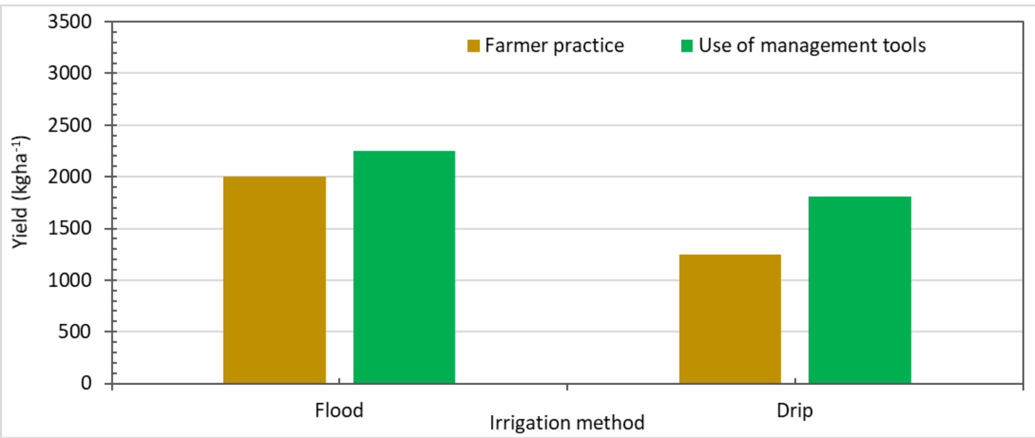


**Figure 9.** Crop yield under flood and drip irrigation method

## 4.5. Irrigation water productivity

Irrigation water productivity increased for all farmers that used the management tools to enhance their decision making in both flood and drip irrigation methods, indicating improved irrigation water use efficiency (Figure 10). Irrigation water productivity under farmer practice was 0.15 $kgm^{-3}$ and 0.25 $kgm^{-3}$ for flood and drip irrigation respectively. This irrigation water productivity under use of management tools increased to 0.21 $kgm^{-3}$ and 0.39 $kgm^{-3}$ for flood and drip irrigation respectively.

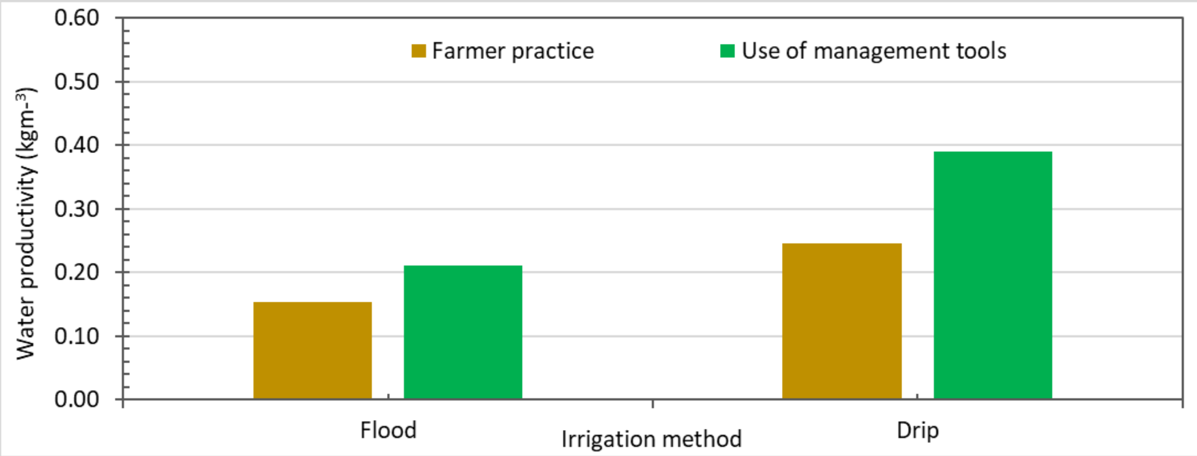


**Figure 10.** Average irrigation water productivity for flood and drip irrigation methods

## 4.6. Crop production income

The crop production income was based on the input (and outputs costs for the farmers for flood and drip irrigation is shown in Tables 10 and 11. The cost were based on the market in nearest town of Beitbridge (Tables 10 and 11). There was increased sales (10%) and income (114%) under the use of management tools compared to farmer practice. The 80 kg crop yield in a 0.2ha plot for self-consumption was included in total yield, as the farmers would have bought the same from the market to enhance their nutrition had they not farmed the crop.

**Table 8.** Summary of income and expenses for the flood irrigation method

| Item | Farmer practice | Use of management tools | Difference (%) |
|---|---|---|---|
| Total Yield (kg $ha^{-1}$) | 2,000 | 2,250 | 13 |
| Total expenses (US$ $ha^{-1}$) | 840 | 771 | -8 |
| Total crop sales (US$ $ha^{-1}$) | 3,681 | 4,141 | 13 |
| Gross Income (US$ $ha^{-1}$) | 2,841 | 3,370 | 19 |

Note: In the calculation of total crop sales the 80kg per farmer plot size of 0.2ha was added to the total yield under the two irrigation methods. The total expenses included the investment of tools. 1 US$ = ZAR 16.30 (Oanda, 2020)

**Table 9.** Summary income and expenses for the drip irrigation method

| Item | Farmer practice | Use of management tools | Difference (%) |
|---|---|---|---|
| Total Yield (kg $ha^{-1}$) | 1250 | 1806 | 44 |
| Total expenses (US$ $ha^{-1}$) | 734 | 717 | -2 |
| Total crop sales (US$ $ha^{-1}$) | 2,301 | 3,324 | 44 |
| Gross Income (US$ $ha^{-1}$) | 1,566 | 2,607 | 66 |

Note: In the calculation of total crop sales the 80kg per farmer plot size of 0.2ha was added to the total yield under the two irrigation methods.
1 US$ = ZAR 16.30 (Oanda, 2020)

# 5. Discussion

## 5.1. Significance of the results

The results demonstrated that use of the management tools (sensors and wetting front detector) in smallholder irrigated agriculture were effective in improving existing both flood and drip irrigated water productivity and production, while minimizing adverse environmental impacts of irrigation drainage and nutrient leaching. For instance, nutrient loss beyond crop root zone decreased by 21% % for flood irrigation, comparable to 62% reported for vegetables under furrow irrigation in Ramotswa (IWMI, 2018). These findings suggest opportunities for use of these simple to read and interpret management tools in resource-constrained smallholder using different irrigation methods. These results were an outcome of an extensive effort that included identification and selection of irrigation sites in and around the Tuli Karoo Aquifer Area, training of the farmers and extension officers on installation and interpretation of readings from management tools, installation of the tools, and data collection, virtual support of farmers and extension officers and data analysis. The results are a major effort to roll out such management tools in smallholder legume (beans) production in Africa. Previous efforts have focused on much controlled experimental fields managed by researchers and other crops like cereals, lucerne, vegetables and not legumes (Maeko, 2003; Pittock and Ramshaw, 2017). More recently, these tools were applied with success in Ramotswa Transboundary Aquifer Area, Limpopo River Basin (IWMI, 2018) and in maize production in Zimbabwe (Moyo et al., 2020). These results are applicable to similar contexts of smallholder irrigation farmers in Africa. Since we monitored for one season, the results are promising to reduce frequency of irrigation but not at the level sufficient for government agencies (ZINWA in this case) to change water scheduling for the whole irrigation scheme as reported in other studies in Africa (Mdemu et al., 2020; Pittock et al., 2020). However, extension staff was interested in the changes that were facilitated by the tools.

## 5.2. Major findings

Five major findings from this report emerged. First, management tools worked successfully, by contributing to a range of positive outcomes that were evaluated. Second, significant irrigated water productivity improvement was realized for smallholder irrigation farmers in the Tuli Karoo Aquifer Area. Third, there was greater positive impact through use of such tools on flood irrigation method than drip irrigation schemes, consistent with findings in Ramotswa by IWMI (2018) on vegetables. In Ramotswa, yield improved by 72% and 25% for furrow and drip irrigation system, respectively. Fourth, yield and income improved following introduction of the management tools. Fifth, the feedback from the experience of the farmers on the use of the management tools. Finally, initial findings in the RTBAA suggest substantial scope for broader application in geographies of similar conditions in Africa where aridity, food insecurity and irrigation are present.

***Finding 1: The less sophisticated management tools worked successfully by informing farmers' learning experience and decision-making in the Tuli Karoo Aquifer Area.*** Success is reflected in reduction in the amount of irrigated water applied, and improvements to the irrigated water productivity by avoiding over irrigation and the associated adverse environmental impacts of nutrient leaching beyond the crop root zone and possibly contaminating groundwater sources. The tools provided an effective learning environment (Moyo et al., 2020; Pittock et al., 2020) for farmers to understand crop soil and water changes, which informs their decision-making on how long should irrigation water be applied without leaching the nutrients. Through social learning (Pittock et al., 2020), farmers worked together to learn quickly and change their practices for reducing crop production failure when exposed to simple management tools.

***Finding 2: Major irrigated water productivity improvemen****t*. Major irrigated water productivity improvement by 59% from 0.25 to 0.39 kg $m^{-3}$ was realized by smallholder drip irrigation farmers that used the management tools. This is comparable with water productivity improvement of 0.19-1.28 kg $m^{-3}$ reported by Moyo et al. (2020) under furrow irrigated maize production. Similarly, Magombeyi et al. (2019) reported in the Ramotswa Aquifer Area that furrow irrigation and water productivity improved by more than 300%, however, for drip it improved by only approximately 50%. Irrigated water productivity increased as more crop yield was produced per unit volume of water put to irrigation and reduced unnecessary irrigation. The seasonal reductions in irrigation frequencies were from 11 to 9 (27 % reduction) for flood irrigation method, while for drip irrigation method it was from 11 to 10 (9% reduction) in irrigated water applied. These reductions in irrigation frequencies were similar to evidence from Mozambique, Tanzania and Zimbabwe (Moyo et al., 2020; Stirzaker et al., 2017) that also applied the chameleon sensors and WFD, but to a cereal crop (maize). In Northern Ghana, water productivity increase ranged from 1.09-3.34 kg $m^{-3}$ for tomato and for onion 4.96-3.36 kg $m^{-3}$ (Adimassu, 2020). The frequency of irrigation decreased from 11 to 9 in the first season monitored and may decrease further in subsequent seasons as reported in Mozambique. Chilundo et al. (2020) reported gradual decrease of irrigation events per season from 11 to 6 in the 6th crop growing season in Mozambique, suggesting a gradual adoption of the learning from the tools and an ongoing experimental learning process as farmers adjusted the timing between irrigations

***Finding 3: More benefits were realized through use of management tools in flood irrigation method compared to drip irrigation method***. On average, the irrigated water productivity improved by 38% for flood irrigation method, while for drip irrigation method it improved by 59%. However, the lower productivity for drip was attributed to frost damage and delayed planting by 2 months, due to pump breakdown that affected the crop. These results are consistent with findings from Magombeyi et al. (2019) who compared furrow and drip irrigation methods in dry area of Limpopo River Basin, and those from Pittock and Ramshaw (2017) who used similar management tools in Mozambique, Tanzania and Zimbabwe.

***Finding 4: Yield improved through use of such management tools.*** Bean crop yield improved by 13% and 44% for flood and drip irrigation methods, respectively. Increased yield resulted in increased income by 114% for flood irrigation. This result is consistent with finding from Ramotswa of yield and income improvement by 35% and 36%, respectively (Magombeyi et al., 2019). In Mozambique yield of green maize increased by 47% in the second season of using the similar tools (Chilundo et al., 2020). Economic justification for adapting the management tools in legume crop production is feasible. However, with delayed planting and other weather hazards such as frost the expected yield can be curtailed, as experienced under the drip irrigation scheme.

***Finding 5: Farmers found the tools helpful in their day to day decision making crop management and were keen to continue using the tools.*** Farmers using both flood and drip reported to have learnt when to irrigate the crop and that the management tools saves water and time. Learning from the monitoring tools contributed to overall farm efficiency and changed farmer practice to a more resource efficient practice. One of the constraints to adoption by farmers reported by Moyo et al. (2019) was the complexity of tools used, of which the chameleon and wetting front detector overcome this with a highly intuitive interface. When asked what should be improved, they indicated that all the farmers must use the tools to experience how they can save water and time. The farmers reported that they needed more tools to cover other farmers and plots in the irrigation schemes. When asked if they wanted to continue using the tools, the farmers indicated they are keen to continue using the tools in the next seasons. However when asked if they got enough support, the farmers lamented that the support could have been improved if it was not for the COVID-19 pandemic restrictions. The challenges the raised by some of the farmers were difficulties in reading the tools, matching of the colour changes due to different nitrate levels in drainage water collected in the WFD, need of smartphone to easily transfer data to the virtual platform for sharing with other stakeholders. The farmers concluded the discussion by expressing their satisfaction that they learnt a lot about water and nutrient management. Another challenge reported by farmers was market access. The farmers grew the bean crop under contract and they were provided with all inputs and they provided labour and water. After harvest the contractor fetches all the yield and sent it to the market and deposit money to the irrigation scheme account, for further allocation to individual farmer accounts. The farmers reported that they could benefit more if they were allowed to sell part of the produce to local market. The importance of market access is also reported in Van Rooyen et al. (2020) who argued for functioning of input and output markets and the information flows between these markets and farmers to ensure higher income from higher crop yields realised from improved water and nutrients management.

***Closing thought**: **Benefits of knowledge-sharing and mutual learning*** Co-learning of researchers, extension officers and farmers was essential for the successful use of the management tools. Researchers, extension officers and farmers learnt from each other through physical interactions and virtually after travel ban under imposed due to COVID-19 pandemic (Box 2). Through use of the management tools, there farmers developed new practices on improving water and nutrient management for enhanced crop yields. Hence, the use of these tools could be an innovation towards more adaptive irrigation practices, which have been limited in Africa, especially under water scarcity and climate change.

**Box 2: The viability of use of such tools in a crisis context like COVID-19 pandemic depends on cooperation and capacity of farmers or farm supervisors and local extension officers.**

From this study we could not get data from two sites in Botswana despite the farmers' assurance that they were keen to use the management tools and extensive provision of virtual assistance and capacitation to the farmers. In Zimbabwe we were able to get results from the farmers because the local extension officers were keen to help farmers increase crop water productivity and ensure that the crop does not fail since the farmers grow the crops under a contract with a local seed company.

Substantial effort was channelled through communicating with telephone and WhatsApp. The farmer learning on site was not impacted but the monitoring and evaluation of the project was a challenge. In Botswana, one of the farmers was keen to evaluate the instruments but the supervisor assigned indicated that he got sick for two months and was not able to provide the data as agreed at the start of the project. However, despite having trained the supervisor and the assistant supervisor, the assistant supervisor was not able to take over and continue to collect data for evaluating the tools. This did not come to fruition. For Zimbabwe, sustained effort was nonetheless needed, as multiple communications channels (WhatsApp, telephone) were employed with persistence to acquire data. This may suggest, even in a 21st century world of virtual engagements and all this technology, there may still be a place for some face-to-face engagement, though less frequently.

Lesson learned on operating in crisis and risk context, is to increase the number of people trained on each site to ensure that if one person is sick or not available, more than three people are capable of taking readings from the instruments. It should make it clear as well that the instruments should be stored where any of the 4 people at the farm can get access, in case the key responsible person is not available. The key person should also indicate to the researcher the alternative person if the key responsible person is not available to collect the data.

Uploading of data is important for researchers to track progress of data collection. For Botswana, when we realized no data was being collected and updated on the platform we contacted the farm supervisor and he indicated that he was sometimes not able to upload the data because of the weak network. Things would have been better if the staff from the Department of Crop Production was allowed to go to field to assist. Unfortunately, after the relaxation of the field visit ban in Bobonong, the contract of staff who was involved in the field work of installing the tools in Smallholder farmer 2 Farm ended in July and this made it difficult to find someone locally to visit the farm and assist the farmers with the challenges of data collection. The data collection in Zimbabwe continued because of the back stopping support to farmers given by the two extension officers. This was not available in Botswana due to the end of contract of the officer from crop production that was supporting the project.

## 6. Conclusion

The use of management tools by smallholder farmers hold substantial potential to improving sustainable irrigated agricultural water use, crop water productivity and production, while minimizing adverse environmental impacts such as nitrate and pesticide pollution in semi-arid areas of Africa. The learning of farmers from using the tools resulted in reduced time farmers spent irrigating, reduced weeding times, which reduced the competition for water and nutrients from weeds, further increasing yield. Significant improvements in crop yield, and water and nutrient savings can be achieved by incorporating the management tools in smallholder irrigation schemes, thereby achieving food security and rural development. In conclusion, five recommendations are offered:

- ***Promote behaviour change rather than technology-dependence.*** Learnings from the tools incentivized labour saving, fuel saving, higher income, and potential less water use in times of scarcity and higher fertilizer efficiency. The learning the farmers acquired was internalised and there was no need to continuously use the tools once the farmers mastered the behaviour of their crops, and water and nutrient management practices.
- ***Increase the number of people with the opportunity to learn from the use of the tools at each site to ensure that if one person is sick or not available,*** more than three people are capable of taking readings from the instruments and continue learning. Local extension officers are key to back stopping the farmers and encourage the use of the instruments by discussing the savings or losses made after each reading. This will capacitate the farmers and increase confidence in the use of the tools.
- ***Continue personal (physical) engagement on technology roll-out when possible, especially early stages of rural focused projects*** Virtual support may indeed have limitations, particularly in initial stages of roll-out in that there is no connection of what the farmer is used to seeing

in the field and what the researcher is interpreting from the data sent to him or her. This is especially so during days when the soil surface looks dry but root zone will still be wet. This results in farmers losing confidence in the use of the tools. There should be more focus to achieving buy-in or commitment from farmers and extension services so that they will see things through even if there is a disruption to external support.

- ***Expand use of soil water management tools in the Tuli Karoo Aquifer Area***. Benefits realized and lessons learned by farmers through use the tools call for expanding their use by finding innovative finance mechanisms to support scaling efforts. This requires training of farmers by local public and private extension officers to capacitate them to interpret the readings from the management tools and build trust on the use of the tools. This might require a workshop to train (train of the trainers) a number of extension officers in each locality and country who will further train and support the farmers.
- ***Farmer learning from use of the tools should be upscaled in similar contexts in Africa.*** The tools facilitate learning for better water and nutrient management throughout the cropping season for enhanced crop productivity, especially for low water efficient irrigation methods, such flood irrigation methods. Flood irrigation method may present a better opportunity than drip for application of the management tools, due to larger gains in water productivity, reduced labour and other measures. With the aim of implementing water and labour efficient irrigation methods such as drip in future, use of management tools may save major volumes of water in many smallholder irrigation schemes in the interim.

***Summing up*** Policy responses of inclusion of the management tools in farmer training programs at the farmer and irrigation scheme scales are key. To ensure sustainability, farmers may be trained to use both water and nutrient tools but when it comes to implementation, one of the tools may be used by a farmer to assist in decision-making to reduce water and nutrient use. Reducing input costs will result in increased income for the farmers, while protecting the agroecology.

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## Annex 1: Field Visit Reports, November 2019 and February 2020

**Date: 2-9 February 2020**

Present:

- Smallholder farmer 1 (farm owner)
- One officer from Bobonong Department of Crop Production
- One IWMI researcher

The researcher introduced the Tuli-Karoo project and highlighted that one of the components of the project was improving smallholder farmer irrigation efficiency using the soil-water and nutrient management tools. The soil-water management tool is the chameleon sensor and the nutrient management tool is the Wetting Front Detector (WFD) and the nitrate testing strips.

Training

Chameleon sensor: The chameleon sensor measures the amount of soil-water at three depths within the soil zone, depending on the crop root depth (e.g., at 20cm, 40cm and 60cm) and indicates the amounts of soil-water by three colours: Blue – the soil is wet and above the soil field capacity; Green the soil is moist and the water is adequate for crop, and the farmer should get ready to irrigate in a day or two; and Red - the soil is dry and the farmers should immediately apply irrigation water to avoid stressing the crop any further.

Chameleon reader: the chameleon sensor is read by a chameleon reader, which has three indicator lights corresponding to sensors at depths of 20cm, 40cm and 60cm. When the reader is connected to the sensor it reads the moisture at different depths and save the three values of soil-water in its memory. When the reader is connected to internet by hot-spotting from a phone, it then transfers or uploads the saved data to the https://via.farm/ platform for sharing with the researcher and other users of the soil-water and nutrient management tools (via community). One reader can be used to read several sensors.

The Wetting Front Detector (WFD): The WFD is a funnel shaped instrument designed to collect drainage from the root zone at an appropriate depth depending on the crop root depth. In this project the depth of installation was 30cm. When the WFD has collected enough drainage an indicator cap pops up. The drainage from the root zone is then collected and tested for nutrients and salt levels. The nutrient levels are an indicator of the nutrients and salts lost in the soil profile beyond the root zone. Ideally the nutrient and salts levels should be low to ensure that most of the nutrient are utilized by the crop and only little is lost beyond the crop root zone. The nutrients lost beyond the crop zone are likely to pollute surface and groundwater sources, thereby affecting the availability of water resources for other uses in the Tuli-Karoo system.

Installation

The management tools were not installed in the field as the farmer has not prepared the field. He indicated that he has ordered seedlings for tomatoes, cabbage and pepper from South Africa and is expecting them end of February 2020, and then he will plant.

However, from recent (02/03/2020) telephonic communication with the farmer, he indicated that he will be planting on the week of 15 March 2020.

Planned crops and area

Present:

- Smallholder farmer 1
- Farm supervisor
- Assistant to the farm supervisor
- One officer from Bobonong Department of Crop Production)
- One IWMI researcher

The researcher introduced the Tuli-Karoo project and highlighted that one of the components of the project was improving smallholder farmer irrigation efficiency using the soil-water and nutrient management tools. The soil-water management tool is the chameleon sensor and the nutrient management tool is the Wetting Front Detector (WFD) and the nitrate testing strips.

Training

The farm supervisor and his assistance were trained on the use of sensors and WFD. However, the farm owner was attended the training and left due to other commitments during the field installations.

Installation

The management tools were installed in the green pepper and tomato fields. The drilling of holes using a mechanical auger for installation of sensors and WFD is shown in Figures A1 and A2. For these fields there was no control plots, hence the performance of the management tools in the currently planted fields will be compared with similar crops, recently harvested (similar season).

However, from recent (02/03/2020) telephonic communication with the farm supervisor, he indicated that data collection on-going well in the two fields.

**Figure A1. Drilling a hole for chameleon sensor installation in Smallholder farm 2, Molalatau area**


**Figure A2. a. Drilling a hole for the installation of WFD, b. Reading soil-water level immediately after installation of the chameleon sensor.**

**Commercial farm**

Present:

- Farm owner)
- One officer from Bobonong Department of Crop Production
- One IWMI researcher

The researcher introduced the Tuli-Karoo project and highlighted that one of the components of the project was improving smallholder farmer irrigation efficiency using the soil-water and nutrient management tools. The soil-water management tool is the chameleon sensor and the nutrient management tool is the Wetting Front Detector (WFD) and the nitrate testing strips.

Training

The farm owner was trained on the use of sensors and WFD. The farmer explained that he is currently using satellite technology from Stanbic Bank to identify and monitor crop stress due to water, and pests and diseases. The satellite imagines are taken every day at 8m above the crop. The farmer indicated that the satellite technology had some shortcomings as it did not provide him with the soil-water levels but the plant response. The farmer was interested in the soil-water and nutrient management tools as they will give more accurate information about the soil-water levels, rather than using the satellite images to schedule irrigation.

Installation

The management tools were not installed in the field as the farmer was still preparing the fields by ploughing down the maize stalks from the previous crop. He indicated that he will planting sugar beans and maize end of February 2020.

However, from recent (26/02/2020) telephonic communication with the farmer, he indicated that he will be planting during the week of 2 March 2020.

**07/02/2020**

**Meeting:**

**Present:**

- 2 Extension officers
- One IWMI researcher

The training on the use of tools was held with two extension officers for Ndambe 1 and Ndambe 2 Irrigation Schemes. The objectives of the meeting were to introduce the Tuli-Karoo project and to train the extension officers on how to use the soil-water and nutrient monitoring tools. The Tui-Karoo project is titled: Conjunctive Surface- Groundwater Management of SADC's Shared Waters: Generating principles through fit for purpose practice (2018-2021).
The aim of the project is to develop conjunctive approaches to surface and groundwater resources management in the Tuli Karoo – Upper Limpopo River Aquifer System, which is shared among Botswana, Zimbabwe and South Africa. There are two main components in this project. The first component is real-time groundwater monitoring and the second component is improving water and nutrient management in irrigation schemes. Hence, the second component was the reason for engaging the extension officers for Ndambe 1 and Ndambe 2 irrigation schemes in Zimbabwe.

Training

The two extension officer were trained on the use of sensors and WFD and how to interpret the readings from the management tools.

**08/02/2020**

**Farmer training in Ndambe 1 and Ndamabe 2 irrigitation schemes, Zimbabwe**

The extension officers accompanied the researcher to the two irrigation schemes for training of the farmers on how the chameleon sensors and Wetting Front Detectors (WFD) are used to enhance the management of soil-water and nutrients in an irrigation field. The farmers highlight that the use of the instruments maybe challenging in the sandy soils as the moisture quickly replenishes and depletes as well (Figure A3).

Installation

The management tools were not installed in the field as the farmers were still harvesting the maize crop. The farmers indicated that they had received seed and fertiliser from SEEDCO, a company that is having contract farming with them. They had planned to plant beans and maize the first week of March 2020.

However, from recent (03/03/2020) telephonic communication with the extension officers, the planting period was changed to second week of March 2020.

Farmers to participate in the study were identified by extension officers and chairpersons of the two irrigation schemes.


**Figure A3. Farmers training for Ndambe 1 – drip irrigation (a) and Ndambe 2 - flood irrigation (b).**

**Figure A4. Farmer training for the Ndambe 1, drip irrigation system**

**Figure A5. Dam water release from the Zhovhe Dam into Mzingwane River for supplying irrigation water to downstream farmers on 7 February 2020, Zimbabwe**

**Figure A6. Water source from a shallow well equipped with submersible pump and diesel pump (backup) and near the Motloutse River, Bobonong (Smallholder farm 1**

**Figure A7. Land preparation in the commercial farm**

**Figure A8. Tractor for land preparation in the commercial farm, Botswana**

## Field visit planning for AgWater solutions component from 2-9 February

Date: February 2020

February 3: Drive to Botswana - Bobonong

February 4: Visit farmer 1; Data collection inputs (water use, electricity bills, fertilizers, seeds, labour – planting, weeding and harvesting) and income; Training, installation of equipment (sensors and rain gauge) and connecting sensors to cell phone (smallholder). These activities will be repeated for every site visited.

February 5: Visit farmer 2 (smallholder)

February 6: Visit farmer 3 (commercial)

February 7: Travel to Beitbridge (staying at Zhovhe Dam)

February 8: Visit Ndambe 2: Flood system near dam

February 9: Visit Ndambe 1: Drip system

February 10: Drive back to South Africa

| 3 Feb Monday | 4 Feb Tuesday | 5 Feb Wednesday | 6 Feb Thursday | 7 Feb Friday | 8 Feb Saturday | 9 Feb Sunday |
|---|---|---|---|---|---|---|
| **Drive from PTA-Bobonong (Bots)** | Install equipment at farmer 1 in Bobonong (Bots) | Install equipment at farmer 2 in Bobonong (Bots) | **Drive from Bobonong (Bots) to Beitbridge (Zim)** | Install equipment at Ndambe 2 near Beitbridge | Install equipment at Ndambe 1 near Beitbridge | **Drive from Beitbridge (Zim) - PTA** |
| Night in Bobonong (Bots) | Night in Bobonong (Bots) | Night in Bobonong (Bots) | Night in Beitbridge (Zim) at Zhovhe Dam | Night in Beitbridge (Zim) at Zhovhe Dam | Night in Beitbridge (Zim) at Zhovhe Dam | |

**Date: 25-28 November 2019**

25/11/2019

Present: Meeting at SPEDU offices

2 Officers from SPEDU

- 2 officers from Department of Crop Production -Botswana
- 2 researchers from IWMI

We held a brief meeting at the SPEDU office in Selebi-Phkwe to decide on the farmers to be visited for the initial selection of Agricultural Water Management (AWM) sites in Botswana. It was decided to visit 2 smallholder farmers and one commercial farmer in Botswana.

**Field visit**

- Smallholder farmer 1Smallholder farmer 1 – Smallholder farm owner
- Farm Supervisor
- Permanent worker

This is an individual farm of 4 hectares and one shallow well.

The farm employs six causal labourers (temporary workers)

The owner of the farm was not present during our visit.

Water shortage: The supervisor reported that there is shortage of water. The shallow well used is 2.5m deep and is located on the river bank of Motloutse River. Hence, during the dry season the water level is very low, as the river surface flow will be dry.

Water storage: The water storage tank at the farm used for irrigation is 30,000 Litres. It takes 3 hours to fill the water storage tank, and an hour to drain the tank by irrigation. The specifications of the pump that pumps water from the storage tank to the field are discharge 4.8-18$m^3$/hr and head 36.6m. One block of field is 60m × 40m = 2400$m^2$

Crop production: The current (2019) crop of cabbage and green pepper did not do well due to water shortage. In early January 2020, the farmer will plant the following crops: cabbage, tomato and green pepper.

Date: 26/11/2019

Present:

- Smallholder farm owner
- Farm Supervisor

This is an individual farm of 6 hectares and two boreholes.

They apply water every day, except when it is raining, due to the very hot weather conditions. When it is very hot, they apply water twice a day, afternoon and night.

Water shortage: The supervisor reported that there is shortage of water, especially from August to December of every year. The two boreholes all 200m deep, and partially penetrated the sandstone formation. Water strikes are at 30m, 120m and 150m. The farmer tried to drill another borehole in 2019, but the final depth of this borehole only 80m.

Market: They market their produce to Mr Veges and Choppies supermarket in Selebi-Phikwe

Water storage: The water storage tank at the farm used for irrigation is 60,000 Litres. Location of the reservoir is: -22.10841$^0$; 28.61872$^0$; Altitude: 666m

Workers: They have 10 permanent workers; 6 from Botswana and 4 from Zimbabwe.

Crop production: The current (2019) crop of cabbage did not do well due to water shortage and diseases. At daily maximum temperatures of 44 degree Celsius, the cabbages were damaged even though they were irrigated day and night. Next year (2020) they will focus on tomato and green pepper crops, but this will need more labourers. They keep the production records for the farm and these could be provided to the researchers at a later stage.

Energy use: the farm spent R200-R300 per day for electricity. They indicated that this electricity bill is expensive, but better than using diesel. They used diesel for pumping water before 2008 when there was no electricity.

Date: 26/11/2019

Commercial farm owner

He brought the farm 3 years ago (2016). Crop production: crops grown are beans and maize. The farmer will plant 180ha of maize on the 1st of February 2020 and 1st of March 2020, he will plant 250ha of beans. The bean crop will be distributed across different centre pivots.

The farmer also complained of high temperatures of about 44 degrees Celsius that result in leaf damage of maize crop.

Crop monitoring: the farmer reported that Stanbic Bank sends him a satellite image taken at 8m above the maize crop every second day. The satellite image is used to monitor crop stress and diseases, and the bank will advise the farmer accordingly if there is stress or diseases on the crops.

Date: 27/11/2019

**Meeting at Beitbridge Rural District Council**

Present:

- Mr Machowa – District Agritex Officer
- Mrs Mahlangu
- Mr Nsingo
- Manuel
- Jonathan

The irrigation schemes in drought prone southern part of the country including the district of Beitbridge were rehabilitated and modernised to boost climate change adaptation methods and enhance agricultural productivity and resilience among smallholder farmers. Other climate change adaptive methods considered include water harvesting, growing drought tolerant crops and varieties, using water efficient irrigation systems such as drip irrigation, dam construction and crop diversification. The funding for these rehabilitations were facilitated in 2017 under the three year Zimbabwe Resilience Programme (US$5.3 million) funded by the United Nations Development Programme (UNDP) and implemented by a non-governmental organisation, CESVI. Benefiting irrigation projects include Bili, Shashe, Jalukanga, Dombolidenje, Tshikwalakwala, **River Ranch, Tongwe, Kwalu, and Ndambe 2**. The overall project objective was to make the communities, local authorities, private partners and extension services be aware of the importance of working together in sustaining these irrigation schemes, to reduce water use and operational costs. CESVI collaborated with agriculture extension services to teach farmers on the importance of using business models to manage their irrigation projects so that they can set money aside for equipment and infrastructure rehabilitation and operation and maintenance. The NGO also helped smallholder farmers to move from flood irrigation to other technologies such as centre pivots, pressurised watering systems and drip irrigation and from low value crops to high value crops like citrus and sugar bean seed production.

The irrigation schemes initially considered for selection included:

- River Range irrigation scheme
- Tongwe irrigation scheme
- Ndambe 2: surface irrigation system
- Ndambe 1: drip irrigation system
- Kwalu: surface irrigation scheme
- Ipai irrigation scheme- surface irrigation system
- Shashe irrigation scheme for citrus trees

River range, Ipai and Shashe irrigation schemes were excluded from the field visits as they were far from the Beitbridge.

We also met the councillor for some of the irrigation schemes.

We were also introduced to– Acting District Administrator. He welcomed us and was happy to work with us on improving irrigation water use efficiency in smallholder farmers.

**Tongwe irrigation scheme**

The scheme was established in 1963 and has a surface irrigation system of 27ha. The scheme has 75 farmers. Each farmer has 0.4ha plot. This 0.4ha takes 10 hours (either 6am-4pm or 6pm to 4am) to irrigate.

Crop production: The maize crop is planted with fertiliser- D and top dressed with ammonium nitrate fertiliser at 2 and 4 weeks or when tasselling. They start planting beans around 15 February of each year. Tongwe River feeds into Mutetengwe River and Mutetengwe River feeds into Mzingwane River.

Challenges:

Market – the farmers do not have a good market for the maize and they sell it locally, while beans they sell them to SEDCO.

Health - Mosquitoes are a problem in the area because of water from the dam and river.

**Ndambe 1 Irrigation Scheme**

Location: -21.86967$^0$, 29.70822$^0$; Elevation: 535m

The scheme has a drip irrigation system. The irrigation scheme area is 9 ha. Each family has three plots of 0.04ha each, to make a total of 0.12ha. There is no possibility of expanding the irrigation area because of the rock and hilly area around this scheme. The scheme uses electricity energy.

Crop production: The crops grown include maize, beans, butternut and watermelons. Nutrient application includes livestock manure and fertiliser.

The irrigation committee consists of 2 women and 5 men. Originally, 30 families benefited from the scheme, but now only 24 families are benefiting from the irrigation as some dropped off from the scheme. The system in the field uses pressure tanks to supply water to the drip irrigation system. The farmers irrigate for 7 hours/day, normally from 8am to 3pm.

**Ndambe 2 irrigation scheme**

It is a gravity –flood irrigation system. Each farmer has 0.4 ha which are divided into 0.2ha on either side of the main canal in the irrigation scheme. Each 0.2ha plot takes 30-35 minutes irrigation time. The farmers each pay $8 per month for water to the ZINWA. The water bill amounts to $304/month. However they said the water allocation can be obtained from ZINWA. The farmers start planting sugar beans early march of every year. We saw the deputy chairperson. The source of water is Zhovhe Dam with a capacity of 132 million cubic metres.

**Kwalu irrigation scheme**

Kwalu Irrigation scheme was established in 1965 and has a total active area of 95ha. The scheme pumps water from the Umzingwane River using boreholes located at the edge of the river banks. The scheme has never had full irrigation of the irrigable 120 ha, even when it was first constructed. The major problem was the pumping capacity that cannot deliver adequate water to meet the total area crop requirements. Each farmer 0.2 ha (0.1ha in 2 blocks). Pivot 1 has 35ha, Pivot 2 has 26ha and Pivot 3 has 34ha. The canals were rehabilitated in 2011. There are 150 farmers in total, but only 95 farmers are active. The source of water is sand water abstraction systems that use 4m-deep boreholes at the edge of the river bank to pump water from the river bed to the field. Crops grown include maize and sugar beans. Maize is grown throughout the year but sugar beans they plant it in February. The market areas for the green mealies include Beitbridge and Makhado along the Beitbridge road.

Challenges: Irrigation water is not enough. They had 6 sand water abstraction schemes and 3 were washed away by floods. Now of the three remaining only two systems are functioning. This reduction in water availability has resulted in farmers reducing the cropping area.

There is also challenge of the army worm that has become resistant to the methalone chemical that they use. This pest results in yield reduction and there is need for effective chemical to destroy this pest.

## From literature research

Ndambe 2:

A non-governmental organisation, CESVI, has started rehabilitating and modernising nine irrigation schemes (Ndambe 2, Bili, Shashe, Jalukanga, Dombolidenje, River Ranch, Tongwe, Kwalu and Tshikwalakwala) in the drought prone district of Beitbridge to boost adaptation strategies to climate change, enhance agricultural productivity and resilience, and livelihoods among smallholder farmers. These projects fall under a three-year (2017-2019) initiative programme called Zimbabwe Resilience Programme funded by the United Nations Development Programme (UNDP) to the tune of US$5.3 million, and includes funding of non-forestry timber projects in Nyanga (Muleya, 2019). The overall idea for the project was to make the communities, local authorities, private partners and extension services aware of the importance of working together in sustaining these irrigation schemes, to use less water and less operational costs, especially after 3 consecutive years (2015-2019) of drought in the area. Some of the climate change adaptive strategies spearheaded by this project include assisting smallholder farmers to move to water efficient irrigation systems such as to move from flood irrigation to centre pivots, pressurised watering systems and drip irrigation, among other modern technologies. Other strategies included water harvesting, growing drought tolerant crops, drip irrigation, dam construction and crop diversification into high value cash crops like citrus and sugar bean seed production (Muleya, 2019). This diversification is encouraged by partnering with partners that are more commercial oriented.

Farmers are encouraged to spend less for their inputs but use sustainable methods to improve productivity; hence this AgWater component contributes to the different elements that will help communities to produce more with minimum water.