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Agricultural Water Management Solutions for smallholder farmers in the Ramotswa Transboundary Aquifer Area

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Executive Summary

Background Rural agricultural development has great potential to alleviate poverty, reduce food insecurity and improve rural livelihoods in Africa. However, in arid areas such as the Ramotswa Transboundary Aquifer Area (RTBAA) in the upper Limpopo, limited and variable water availability constrains agricultural production. Hence, there is a need to enhance agricultural water use efficiency to maximize the benefits of limited water resources. Monitoring tools that underpin a learning system of practices are necessary to increase soil-water and nutrient management capacity and the profitability of smallholder irrigation.

Objective The objective of this report was to assess the impact of simple water and nutrient-saving tools (chameleon sensor, wetting front detector and electrical conductivity meter) to achieve improved soil-water-nutrient-salt management for greater yield and gross irrigated water productivity for smallholder irrigation farms. We also identified the constraints to adoption and the potential for outscaling of tools amongst smallholder farmers.

Methods Case control, and before after design controls were used. A comparison of experimental vs. control field plots was used to assess the impact of soil-water and nutrient monitoring tools. The replicated control design, where each experimental treatment was near a control treatment was used. Experimental treatment was a field where farmer soil-water and nutrient applications are informed by soil-water and nutrient monitoring technologies. A control was taken as routine farmer management practice of soil-water and nutrient applications, i.e., where monitoring technologies were not used to inform agricultural water management practices.

Schemes and plots Three irrigation schemes selected in this study were Motlhaka in South Africa and Mogobane and Glen Valley in Botswana. Motlhaka irrigation scheme uses furrow irrigation system, while Mogobane and Glen Valley use drip irrigation. Four plots were selected in each scheme. The irrigation water sources were groundwater in Motlhaka and Mogobane and treated domestic wastewater effluent from Gaborone City in Glen Valley. Cabbage crop was monitored in Motlhaka, Mogobane and Glen Valley, while only beetroot was monitored in Mogobane and only tomato in Glen Valley.

Measuring impact Seven indicators were applied to evaluate impact of water, nutrient and salt monitoring tools on the yield, soil nutrient loss (environment), soil salt loss and net income (economy) in irrigated agriculture:

- water use and frequency of irrigation
- nutrient loss beyond root zone
- soil salinity levels
- labour
- crop yield
- gross irrigated water productivity
- crop production income

Impacts were assessed using the difference-in-difference method, where the changes in selected indicators on the experimental fields are compared to changes on the control fields of the project. Impact at plot and scheme levels was inferred if the changes among the experimental fields were

significantly more favourable than changes among the control fields. This analysis also considered the moderating variables that might affect this comparison, such as soil type. Assessment of significance of differences between control and experimental plots was tested using the paired *t*-test.

Results: *Significant irrigation water and nutrient savings under smallholder farming* Overall, the results showed significant water savings, nutrient loss reduction and improved yield and gross irrigated water productivity for experimental plots compared to control plots under diverse environmental conditions. Water savings resulted in reduced energy expenses and labour cost for irrigation, weeding and chemical spraying. The two irrigation systems, furrow and drip benefited to different degrees from the use of the monitoring tools. Yield may not be a best indicator to convince drip farmers of the impact of monitoring tools but may be a good indicator for those using furrow.

Potential for use of monitoring tools in smallholder contexts Ultimately, this work has demonstrated the potential for use of wetting front detectors (WFD) and chameleon sensors in smallholder irrigation agro-ecological conditions with relatively low technology can increase productivity and profitability through improved management of water, nutrients and salinity. This results in increasing food security. The study assessed diverse environmental conditions and irrigation water sources and demonstrated that the current water quality does not have negative impacts on crop production.

Conclusions Soil-water monitoring tools hold substantial potential to improve smallholder irrigated agricultural water productivity and production, while minimizing adverse environmental impacts in semi-arid areas of Africa. Significant improvements in gross irrigated water productivity can be achieved by incorporating the monitoring tools in smallholder irrigation schemes. The use of these monitoring tools can be applied at a broader scale in similar semi-arid areas to help reduce irrigation water and nutrient losses in smallholder farming. Ultimately, five recommendations are offered:

- *Expand use of soil water monitoring tools in the RTBAA*. Benefits of reduced water use and profitability realized through use of soil water monitoring tools call for expanding their use in the RTBAA. Their use can be advanced through partnering with the local departments of agriculture and any NGOs that are supporting agriculture.
- *Irrigated water productivity improvement, reduced nutrient losses and relative low cost of the acquiring the tools are incentives for the use of the monitoring tools*. These benefits result in contribute to food security and protection of the environment through reduction in polluted irrigation drainage.
- *Special Focus should be on rolling out the monitoring tools to furrow irrigation systems.* Perhaps counterintuitively, furrow may present a better opportunity than drip for application of soil water monitoring tools, due to larger gains in water productivity and other measures.
- *Explore opportunities for use of such tools in contexts similar to the RTBAA. Is* may be worthwhile to undertake a mapping exercise to find areas with similar conditions for possible broader scale application of the monitoring tools.
- *More research is required in other areas such as sprinkler irrigation system and other vegetable (e.g., high value green and red peppers and watermelons) and cereal crops*. There is need to expand and assess the performance of the monitoring tools under different seasons, climatic conditions and soil types.

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List of acronyms

DWS: Department of Water and Sanitation

K: Potassium

N: Nitrogen

P: Phosphorus

NGO: Non-Governmental Organization

RTBAA: Ramotswa Transboundary Aquifer Area

US$: United States Dollar

VIA: Virtual Irrigation Academy

WFD: Wetting front detectors

ZAR: South African Rand

1. Introduction

Achieving food security, farm profitability and climate resilience in Africa In rural Africa, agricultural development is a major pathway toward food security, farm profitability and climate resilience. Despite the small area of irrigation, the value of irrigated agriculture in sub-Saharan Africa is about 25% of the total agricultural output (Stirzaker et al., 2017). But agricultural development requires significant amount of water that should be applied timely. Knowing when and what amount to irrigate constitute irrigation scheduling (Maeko, 2003) that farmers exercise by intuition, experience or measurement. However, water scarcity is increasing worldwide and global climate change (Adeyemi et al., 2017) may further increase irrigation water demand due to a greater variation in annual precipitation amounts, resulting in tighter regulation of agricultural water use and more effective irrigation scheduling. In regions of scarce and variable water availability such as the Ramotswa Transboundary Aquifer Area (RTBAA), shared by Botswana and South Africa it is critical to stretch limited water resources. One way to stretch available water resources is development of irrigation practices that increase irrigated water productivity through efficient soil-water, nutrient and salinity management but do not compromise crop quality, yield and environmental integrity.

Soil-Water Monitoring Tools may improve agricultural water management Simple tools for monitoring soil-water and the salts it contains have been used by irrigators to improve crop production, save water and reduce nutrient loss, protecting the environment (Bjornlund and Pittock, 2017). These tools include wetting front detectors (WFD) and chameleon sensors (Bjornlund and Pittock, 2017; Stirzaker et al., 2005). Studies on improving water use efficiency have been reported elsewhere in Omica, Italy and Memphis and San Diego, USA advanced wireless sensor network of Libelium environmental and soil moisture sensors (Zaragoza, Spain) were successfully deployed on a commercial maize farm to support irrigation decisions. The sensors were connected to a spatial geo-referenced decision support system which enabled specific portions of the field to be irrigated according to a set of management options (Adeyemi et al., 2017). Stirzaker et al. (2005) has also reported success when the tools were applied in Australia on surface drip, buried drip, fixed sprinkler, centre pivot, and mini-sprinkler irrigation for annual and perennial crops.

Investigations underway on potential for soil-water monitoring tools in Africa Studies to reduce irrigation water use have been applied in Mozambique, Tanzania and Zimbabwe (Pittock and Ramshaw, 2017). These studies have focused on improving plot and irrigation scheme management, including better practices for fertilizer use, use of high yielding seed varieties, soil fertility management technologies, on-farm water conservation techniques, irrigation scheme modernisation, erosion control, pesticides and herbicides through training and demonstration in the irrigated plots. These studies reported a shortage of skills to capitalise on existing smallholder irrigation infrastructure. At Kiwere scheme, in Tanzania and Mkoba scheme in Zimbabwe the use of chameleon and WFDs in over 40 experimental plots under cereal maize resulted in optimization of soil moisture and nutrient use for crops (Pittock and Ramshaw, 2017). In South Africa, using WFD and chameleon sensor is being tested on commercial farms on onion in the Western Cape, macadamia nut and sugarcane in Mpumalanga and groundnuts and maize in North West (Stirzaker et al., 2017).

Existing work on adoption of technologies to improve soil-water and nutrient management has not focused on smallholder vegetable production and to groundwater and treated wastewater

irrigation water sources. From our literature search (Drummond, 1990; Drummond and Manson, 1993; Speelman et al., 2009; van Averbeke et al., 2011), no study has focused on improving existing irrigation water use from smallholder vegetable contexts or in groundwater-based irrigation schemes. The tools have been reported for cereal crop only under smallholder farming and for high value crops such as macadamia nut and sugarcane under commercial farming with high human and technical resources. In the RTBAA, the only studies that have been carried out in Glen Valley, which focused on assessing the health risks of wastewater use for crop production from samples of effluent, soil and vegetables (Dikinya and Areola, 2009; Monyamane, 2011).

1.1 Report objectives

Report Objectives The main objective of this report is to test the impact of water and nutrient-saving tools (chameleon sensor and WFD) to achieve improved crop yields with reduced water and nutrient losses for smallholder farmers in the RBTAA where groundwater is the main irrigation water source. Additional objectives include:

- To assist farmers to monitor the benefits of adopting new water and nutrient management practices worthy of protecting the environment
- To identify the constraints to adoption and the potentials for outscaling the use of water and nutrient monitoring tools amongst smallholder farmers

2. Study sites

This section presents a brief description of RTBAA and each of the irrigation schemes in the study area.

2.1. Ramotswa Transboundary Aquifer Area (RTBAA)

Ramotswa Transboundary Aquifer Area (RTBAA) The Ramotswa Aquifer corresponds to the Ramotswa dolomitic aquifer extent mapped based on surface geology. RTBAA was used to capture areas in the subsurface that are hydrologically linked to the aquifer, but which lie outside the dolomitic aquifer boundaries delineated based on surface geology (Figure 1). The Ramotswa Aquifer is in North West Province in South Africa and in the South East District in Botswana. The aquifer supplies water for different uses that include domestic, livestock and irrigation.

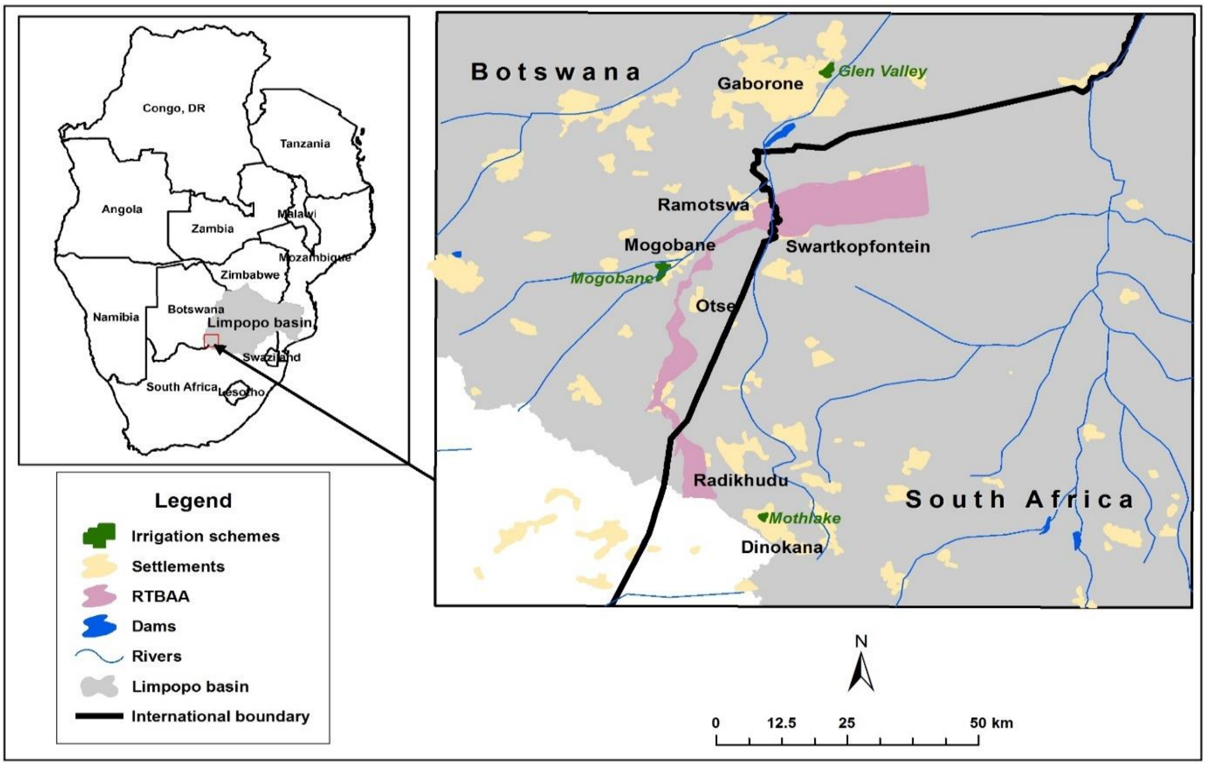

Figure 1. Location of the study area in Botswana and South Africa

Irrigation schemes Three irrigation schemes in the study area were selected based on four criteria. Four criteria used were farm size, purpose for production, presence of smallholder farmers, and availability of baseline information of farms. Only a few potential sites in and around the RTBAA met these criteria. Farms greater than 2 ha were of interest because of their high water abstraction rate, productivity and the advantage to accessing public subsidies/credit facilities. Therefore, these farms have greater capacity for irrigation development. Purpose of production focused on smallholder (1-10ha) to large-scale commercial farmers with incentive for efficiency including agricultural water management improvements. Presence of smallholder farmers was important as they contribute to food security at all levels (household, local and national), employment, poverty alleviation, and economic growth. Farms with baseline information such as crop yields, agronomic practices (fertilizer application rates, weed/pest management), water use and cost of energy for production provided a reference point against which the performance of monitoring tools were evaluated. The following section briefly presents the irrigation schemes selected.

2.2. Motlhaka Irrigation Scheme in South Africa

Motlhaka Irrigation Scheme in South Africa The Motlhaka Irrigation Scheme with an area of 80 ha, was established in the early 1980s with a primary purpose for alleviating food insecurity and poverty within the Tribal Trust Land of Dinokana, South Africa. The irrigation scheme has 60 farmers (18 are youths), with 36 females and 24 males, each owning plot sizes ranging from 10 m by 20 m to about 20 m by 50 m. Several farmers grow same crop simultaneously for easy of marketing of the produce. The scheme is operating at less than 30 % (20 ha) of its original size due to challenges to do with infrastructure and water resources. The major source of water is the Dinokana eye (a spring that flows throughout the year, with a yield of 5 184 m^3/day). The eye also supplies portable water to nearby villages. Additional water comes from two boreholes developed with support from the government. However, these boreholes could not meet the water demand as they lack sufficient maintenance. The irrigation scheme uses furrow irrigation and water is conveyed to the scheme through canals. The crops cultivated include maize, cabbage, tomatoes, beetroot, lettuce and pumpkins. During periods of low flow (e.g., February 2018) tension arises between the livestock owners and the crop farmers due to shortage of water. This tension has been reported to traditional authorities (*Induna*) and the Department of Agriculture. The livestock owners want the crop farmers to stop farming and save water for livestock. There is no written irrigation schedule, hence, every farmer irrigates whenever he wants to, as long as he coordinates with the fellow farmers at that time. The challenge arises when there is peak demand for irrigation as farmers usually enter into conflicts about the irrigation scheduling as some farmers either over-irrigate or under irrigate, depending on their location from the main irrigation water supply canal. Motlhaka Irrigation Scheme layout is shown in Figure 2.

Figure 2. Motlhaka irrigation scheme layout

2.3. Mogobane Irrigation Scheme in Botswana

Mogobane Irrigation Scheme in Botswana Mogobane Irrigation Scheme has an area of about 102 ha and is managed as a Community Trust in Botswana. The Ba-Malete Development Trust appointed scheme manager for day-to-day management of the scheme. No individual farmers own plots in the irrigation scheme as it is operated as one entity. However, only 10 ha is developed for cultivation mostly due to lack of adequate water supply. The scheme was constructed in 1942. The irrigation scheme is subdivided depending on the crops grown in a particular season. Irrigation water is supplied from groundwater through two boreholes installed in the scheme in 2015 and 2018. Drip irrigation kits are used in the scheme. Further, the scheme has installed nets to prevent infestation of pests and diseases on 1 ha of irrigable land. Tomatoes are mostly grown under the nets. Crop cultivated by farmers include butternut, cabbage, spinach, green pepper, tomatoes, wheat, maize, cowpea, potatoes and date palms. The scheme has a higher proportion of land per year for butternut (23 %), beetroot (19 %), cabbage (14 %) and maize (10 %). The scheme is utilized in the months of May, August and September and the maximum area under cultivation is approximately 4 ha. According to the scheme manager, irrigable area was limited by water and capacity of the pump before a second borehole was added in 2018. Two types of crops (cabbage and beetroot) were monitored in this scheme. The irrigation scheme layout is shown in Figure 3.

Figure 3. Mogobane Irrigation Scheme layout

2.4. Glen Valley Irrigation Scheme in Botswana

Glen Valley Irrigation Scheme in Botswana The Glen Valley Irrigation Scheme (Figure 4), developed to fight poverty in Botswana is estimated at about 135 ha of the designated 203 ha of Glen Valley land. The 135 ha area is occupied by about 47 farms of different sizes (1-10 ha) that produce various crops. The estimated water use by the scheme is approximately 1500 $m^3$of wastewater per day, with 90 % of the farmers using drip irrigation system, while the remaining 10 % are using sprinkler irrigation (Monyamane, 2011). Drip irrigation is the recommended because unlike the sprinkler system it does not introduce aerosols into the air. The scheme employs about 100 permanent staff with an additional 100 casual staff being employed during high labour demand periods such as planting and harvesting (Monyamane, 2011). Crops cultivated by farmers include tomato, spinach, olive, green pepper, okra, maize, lucerne, butternut squash, water melon, cabbage and lettuce. Cultivated crops exclude root crops as they are presumed to pose high risk of contamination from effluent. Further, farmers use drip irrigation virtually exclusively, as this is presumed to present a reduced risk of contamination. The irrigation water source comes from secondary treated wastewater effluent. Farmers do not pay water fees neither do they pay for pumps and water storage, but the Botswana Department of Agriculture.

The only major infrastructure investment by farmers is in the piping and control gear for drip irrigation. Some problems the farmers encounter during production include unreliable water supply, frequent burst of pipes, post-harvest losses and slow response of the Government to maintenance and water supply problems.

Figure 4. Glen Valley Irrigation Scheme layout

A summary of the characteristics of the irrigation schemes is shown in Table 1.

Table 1. A summary of the characteristics of the three irrigation schemes

Scheme	Year established	Total area (irrig. area) -ha	No. of farmers	Water source	Irrigation type	Crops	Challenges
Motlhaka	1980	80 (20)	60 (18 youths)	Spring/ borehole	Furrow	Butternut, cabbage, beetroot, maize, tomatoes,	Old infrastructure, water loss from furrows, limited water resources, some farmers either over-irrigate or under irrigate, Tension between the livestock owners and the farmers due to shortage of water
Mogobane	1942	102 (10)	-	Borehole	Drip	wheat, maize, cabbage, spinach, green pepper, cowpea, potatoes and date palms	Limited water and capacity of the pump
Glen Valley	-	203 (135)	47	Wastewater effluent	Drip	tomato, spinach, olive, green pepper, okra, maize, lucerne, butternut squash, water melon, cabbage	Unreliable water supply, frequent burst of pipes, post-harvest losses, slow response of the government to maintenance and high energy costs

3. Materials and methods

3.1. Methodological framework

Experimental and Control Plots A comparison of performing control versus experimental field plots was used to assess the impact of soil-water and nutrient monitoring tools. The replicated control design, where each experimental treatment was near a control treatment was used. A control was taken as farmer common management practice of soil-water and nutrient applications, i.e., where monitoring technologies were not introduced. Experimental treatment was taken to be a field where farmer soil-water and nutrient applications are 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 assumes that conditions such as soil type and fertility 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 called before-and-after design (Kramer and Font, 2017).

Assessing impacts The impacts were assessed using the “difference in difference” method, where the changes in selected indicators 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 moderating variables that might affect this comparison, such as soil type.

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, relatively large experimental plots (0.2-0.5 ha) were selected for monitoring. Motlhaka: In this irrigation scheme, three plots were selected. Only one crop and three farmers were randomly selected and monitored for the winter growing season. The number of plots selected was constrained by the limited monitoring tools. The only winter crop selected by the farmers was cabbage. These plots were managed the same way. Mogobane: Four plots were randomly selected for monitoring from the eight plots planted. Two crops monitored were cabbage and beetroot. Glen Valley: Out of the 47 farmers, two female farmers were selected to participate in this study. Four plots were randomly selected with two additional historical controls for tomatoes and cabbage selected from previous (January- April) crop season of 2018. Two cabbage plots were randomly selected from Mrs Mandizha’s farm, while two plots (tomato and cabbage) were selected for monitoring from Mrs Dineo’s farm, managed by a male manager.

A summary of the selected sites and water sources is shown in Table 2.

Table 2. Summary of selected sites, control types and water sources in the study area

Scheme	Plot	Experimental treatment (ha)	Concurrent control (ha)	Historic control	Irrigation water source	Crop
Motlhaka	1	0.50			Groundwater	Cabbage
	2		0.50		Groundwater	Cabbage
	3		0.20		Groundwater	Cabbage
Mogobane	1	0.50			Groundwater	Beetroot
	2		0.50		Groundwater	Beetroot
	3	0.50			Groundwater	Cabbage
	4		0.50		Groundwater	Cabbage
Glen Valley	1	0.40			Wastewater effluent	Cabbage
	2		0.40		Wastewater effluent	Cabbage
	3	0.30		0.25	Wastewater effluent	Tomatoes
	4	0.40		0.40	Wastewater effluent	Cabbage
Total	**11**	**2.60**	**2.10**	**0.65**		

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 chameleon readers were used in data collection. The minimum total cost of all these tools was US$ 215 (1ZAR = 0.07US$), as at 12 December 2018. The costs varied per farm depending the required units of each tool. Unit cost of the tools is provided in Appendix 1. The mechanical WFDs were installed at 0.3m depth to collect the soil-water drainage used to test nutrient loss. 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. The instruments installed in each plot were a WFD and chameleon sensor (Table 2). Each scheme had a reader to read, store and upload data through wifi from the sensors. A box of nitrate strips for 100 nitrate tests using the colorimetric method was also required for each scheme. The monitoring period covered one crop growing season and started in 1 March and ended in 31 August, 2018.

3.3.1. 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. The farmers uploaded the collected data from the sensor reader to a website, VIA (Virtual Irrigation Academy - https://via.farm/). 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 assess what went wrong in terms of soil-water and nutrient management. From the discussion corrective measures were identified and implemented by the farmer in these days or in a following crop season.

3.4. Indicator selection and population

This study evaluated impact of water, nutrient and salt monitoring tools on the yield, soil nutrient loss (environment), soil salt loss 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 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 4.

Table 3. Indicators measured and sources of information

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).	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, borehole and from wastewater effluent pumped to the field. For irrigation canals, the discharge was estimated by taking several measurements of velocity of flow using velocity flow meter (Global Water Flow Probe FP211 - Global Water Instrumentation, Inc. 2009) and then multiplying by cross-sectional area of the canal. Several velocity readings were made and an average was used in the estimation of the canal water discharge to the field.

From boreholes and wastewater effluent, the irrigation water discharge was measured by taking several measurements of time taken to fill a 20-litre bucket. 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. The four drip nozzles were selected to cover 20%, 50% and 80% of the field length. An average discharge volume per drip nozzle was then multiplied by the total nozzles in the plot to estimate the total irrigation volume supplied to the field per irrigation period.

The frequency of irrigation for all monitored plots in the three schemes was calculated by counting the number of irrigation times from planting to harvest. Under the experimental plot, the water management practice or 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 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 and dry soil, respectively. If all the lights at three depths are blue, it indicates over-irrigating.

One chameleon sensor was installed in each plot due to the small area (< 0.5 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 three macro nutrients are nitrogen (N), phosphorus (P) and potassium (K) and lack of these nutrients along with micronutrients results in crops with stunted growth and poor leaf colour. Nitrate does not bind to soil particles, hence it moves with the irrigated water. If too much water is applied, and the excess drains beyond the root zone, then nitrate will be carried down with the draining water and wasted. 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. WFD funnel captures drainage from the soil root zone. One WFD was installed in each plot. 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. Soil salinity levels

Salinity is the accumulation of excess salts in the soil (Shrivastava and Kumar, 2015) that limits the crop productivity because most -crops are sensitive to salinity. Salts accumulate on the soil surface due to excess moisture, improper crop management and soil and geologic land characteristics. Inefficient management of water resources combined with increased evaporation potential, draws salt to the soil surface resulting in reduced crop growth of most cash crop plants. It was important to check salinity levels in the plots irrigated by wastewater effluent over the years. Salinity was measured by an electrical conductivity meter. The colour patterns for salinity levels from low to high were: green, <1.0 dS/m – salinity acceptable to most plants; yellow, 1.1-1.8 dS/m; brown, 1.9-2.9 dS/m and red, 2.9-4 dS/m – salinity a potential problem for most plants.

3.4.4. Labour

Labour (family or hired) or people-power is an important and costly farm input from land preparation to harvesting that needs to be efficiently used. Efficient use of agricultural labour releases labour to production of other goods and services, as fewer workers or hours per day are needed to produce the food that society requires. 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.

3.4.5. 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. 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.

3.4.6. *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 can be assessed from three broad perspectives, i) physical water productivity (crop output per unit of total water consumed, 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 we assessed the gross irrigation water productivity using records of amount of water applied not water consumption and crop yield from each plot.

3.4.7. *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. The higher the income the more profitable the irrigated agriculture businesses.

3.5. Assessment of significance of differences.

After determining crop yields, nutrient loss and other indicators from control and experimental 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, as the population set has intrinsic differences that are not by chance. Further, when calculated p is less than 0.05 then the result is significant at $p < 0.05$.

4. Results

4.1. Water use and frequency of irrigation

Water use per hectare Mean water use per hectare from control and experimental plots is shown in Figure 5. There is higher water use for control plots when compared to experimental plots. On average 40 % of water savings were realized from the experimental plots.

Impacts on plots with furrow irrigation The experimental plots under furrow irrigation showed huge water saving benefits (50%) compared to the control (Figure 6). Moderate water savings (28%) were realized for drip irrigation when the monitoring tools were implemented. Comparison of results from control and experimental plots for furrow irrigation show that the t-value is 3.28 and p-value is 0.015. This result is significant at $p < 0.05$.

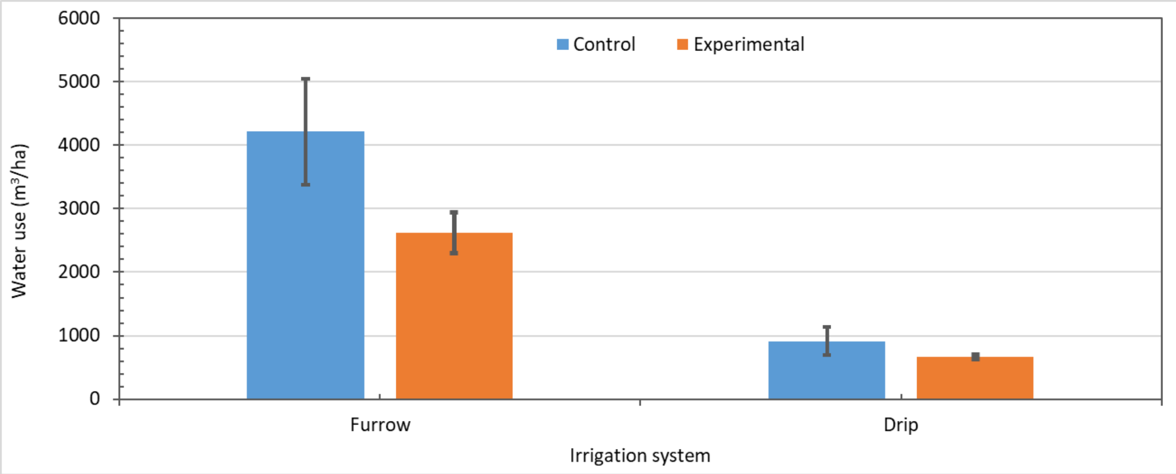

Figure 5. Mean water use per hectare for control and experimental plots for drip and furrow irrigation systems. The error bars show the standard deviation.

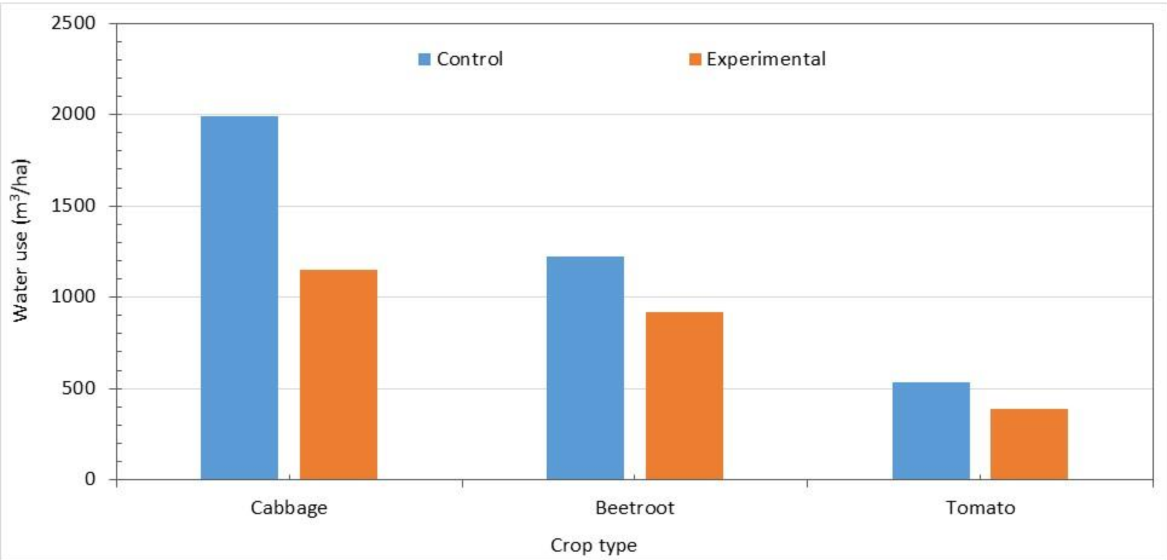

Figure 6. Water use per hectare for control and experimental plots for drip and furrow irrigation systems

Frequency of irrigation There is lower mean frequency of irrigation in experimental plots compared to the control plots (Figure 7a). The frequency of irrigation decreased by 29% for experimental plots. The frequency of irrigation can be affected by the weather, soil type, farmer soil moisture visual tolerance, duration of irrigation, type of crop and growth stage. On average the frequency of irrigation under furrow is significantly (p< 0.02) lower than that under drip irrigation at $p < 0.05$ (Figure 7a). This could be related to the large volumes of irrigation water used under furrow irrigation. However, there is no statistical significant (p= 0.059) difference in frequency of irrigation for crops under drip at $p < 0.05$ (Figure 7b).

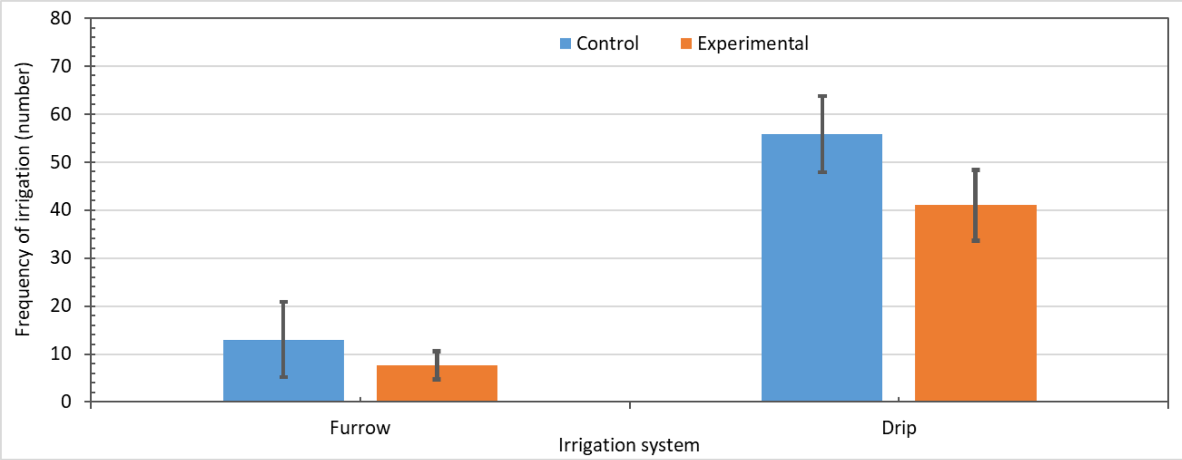

Figure 7a. Mean frequency of irrigation for control and experimental plots for drip and furrow irrigation systems.

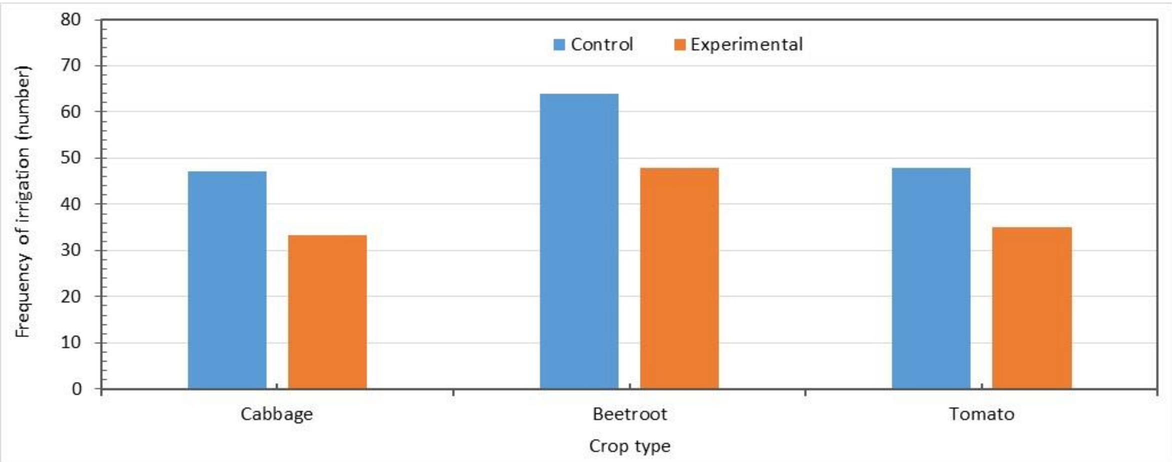

Figure 7b. Mean frequency of irrigation by crop type.

4.2. Nutrient loss beyond root zone

Comparison of nitrate loss between the experimental and control plots showed the control plots had higher nitrate loss beyond the crop root zone at 0.3m depth below the ground surface. There was a huge reduction in nutrient loss of 62% when comparing the control and experimental plots (Figure 8a). This reduction in loss ensures the crop access to most of the nutrients (either inherent or applied) for increased crop health and yield. Over-irrigation resulted in high nutrient leaching beyond the root zone that could cause nitrate pollution to groundwater. There was significant difference (*p*-value is 0.008) of cumulative nitrate loss from drip and furrow systems at $p < 0.05$ from planting to harvest (Figure 8a). Nutrient savings were realized from drip irrigation compared to surface furrow irrigation. Disaggregating the nutrient loss per crop type, showed insignificant difference (*p*-value is 0.070) (Figure 8b).

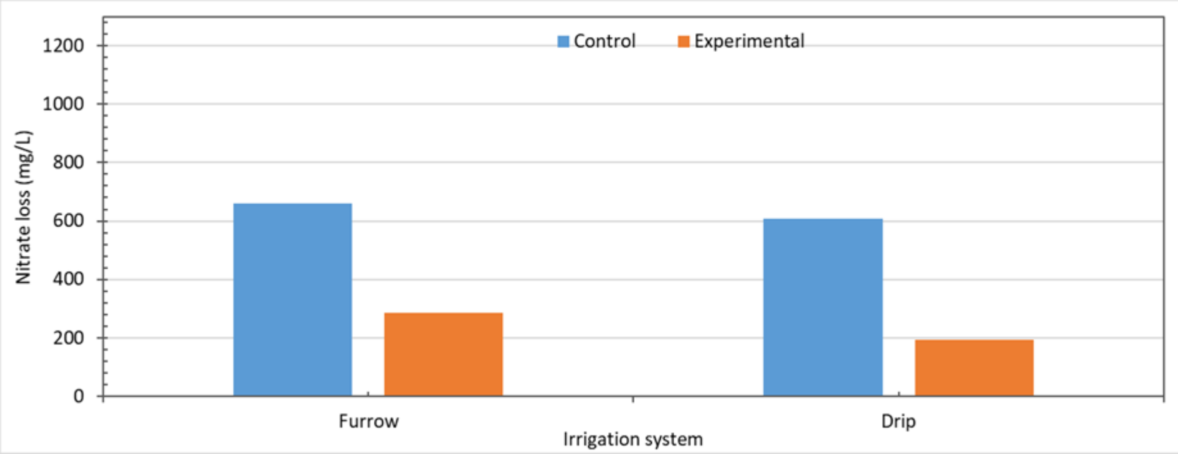

Figure 8a. Average nitrate loss from planting to harvest for drip and furrow irrigation systems

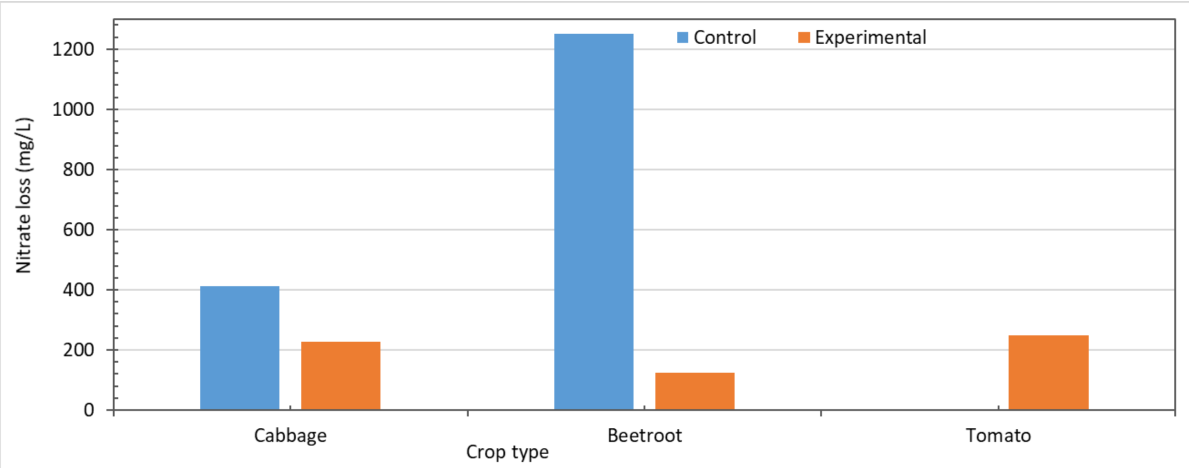

Figure 8b. Average nitrate loss per crop type from planting to harvest

4.3. Soil salinity levels

There is significantly higher salt accumulation under control plots than experimental plots ($p < 0.05$) (Figure 9a), indicating low risk of salinity impact when monitoring tools are used. Drip irrigation system can maintain high soil-water potential that minimizes the effect of salinity (Pescod, 1992). Dikinya and Areola (2009) reported similar results of 0.316 dS/m in the study area in Glen Valley scheme. In most experimental plots, no drainage was collected to enable salt testing, hence this could also mean there was build-up salts in the root zone. The built up of salts could be dislodged by any over-irrigation or heavy rainfall event. There is no significant difference (t-value is 2.18 and p-value is 0.059) in salt accumulation when crop type are compared at $p < 0.05$ (Figure 9b).

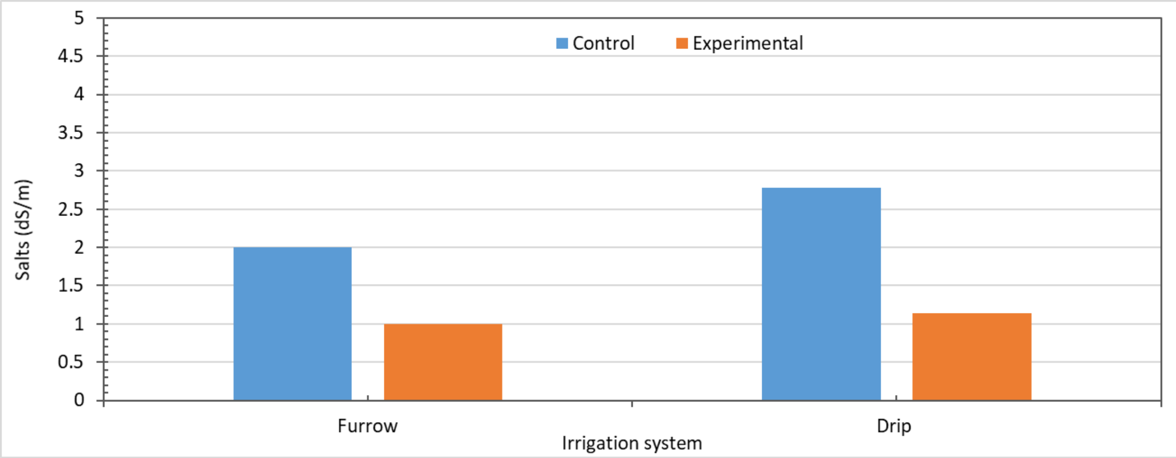

Figure 9a. Average soil salts accumulation under control and experimental plots

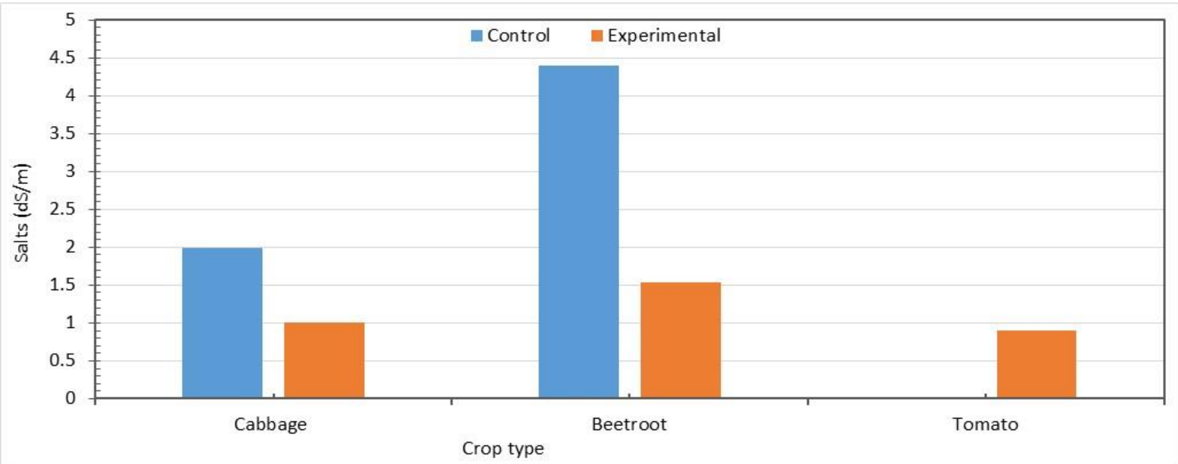

Figure 9b. Average soil salts accumulation under control and experimental plots per crop type

4.4. Labour

The overall labour cost per hectare for experimental plots was lower than that from the control plots in Figure 10a. However, the result is not significant (*p*-value is 0.438). The labour savings come from reduced frequency of irrigation, chemical spraying and weeding, and the wider standard deviation indicates potential to reducing further the labour costs under drip irrigation system

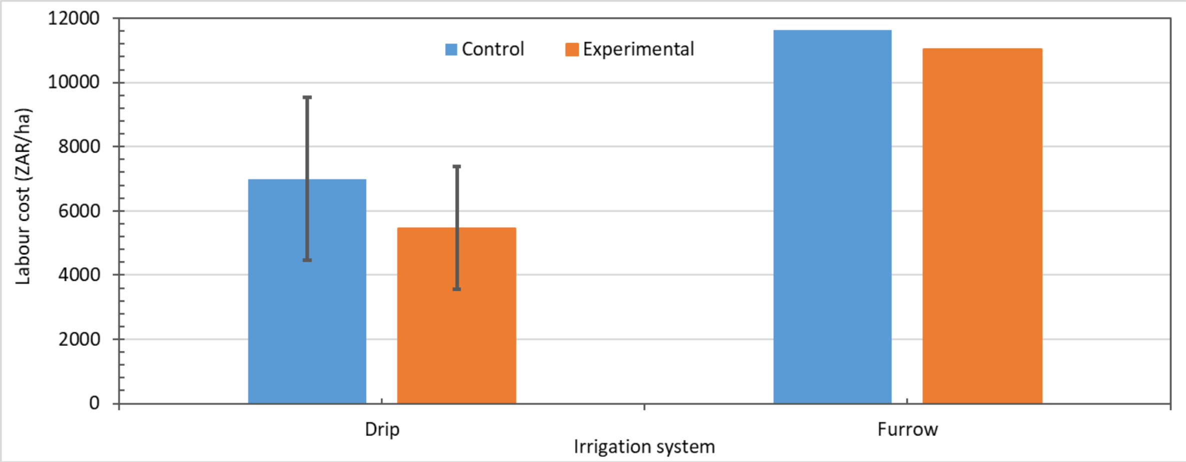

Figure 10a. Labour costs per hectare for control and experimental plots

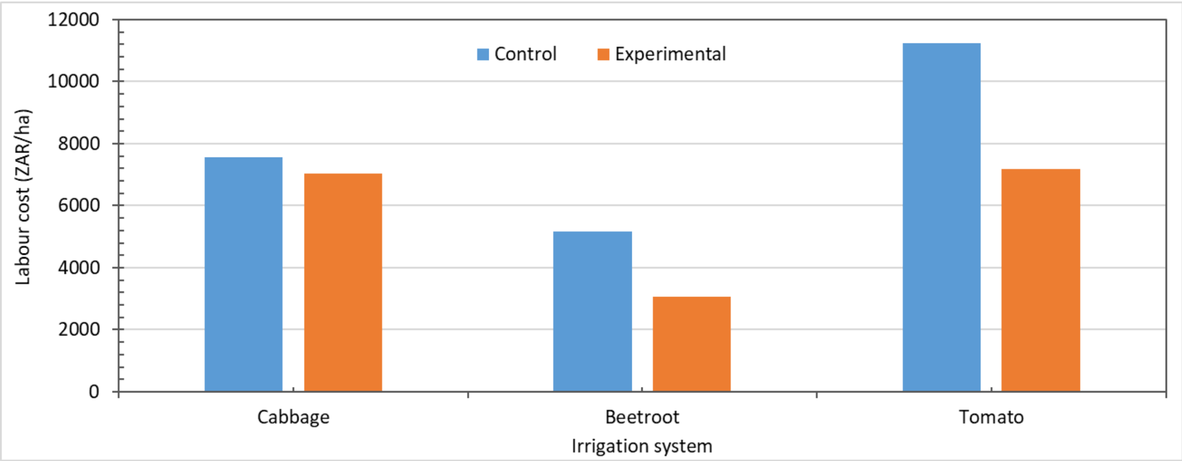

Figure 10b. Labour cost per hectare per crop type

4.5. Crop yields

The overall, crop yield/ha improved by 35% for experimental plots compared to control plots (Figure 11a). The higher standard deviation for experimental plot under furrow showed more opportunity for improvement compared to drip which could be already performing at optimum levels in Figure 11a. Yield variation per crop type (Figure 11b) is not significant (*p*-value is 0.215) at $p < 0.05$.

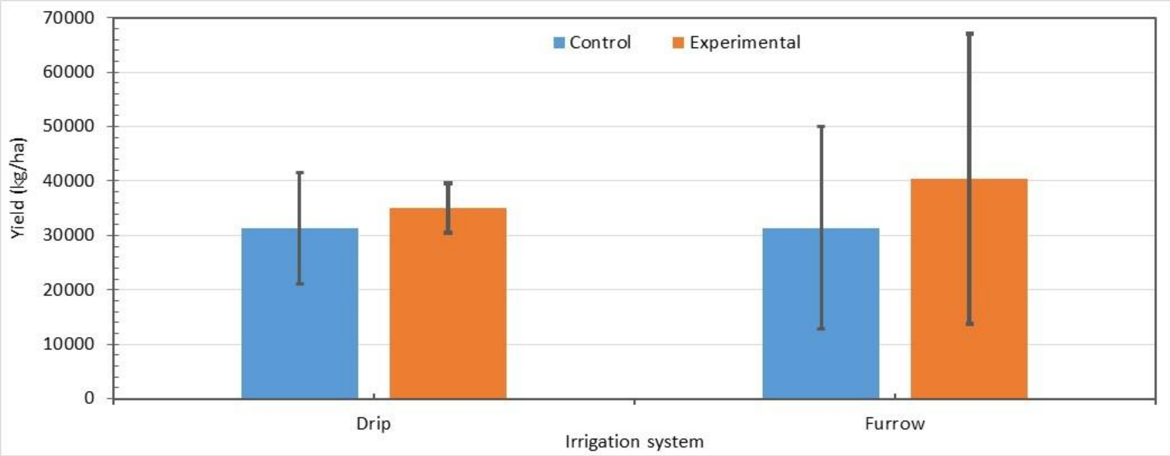

Figure 11a. Crop yields per hectare for control and experimental plots

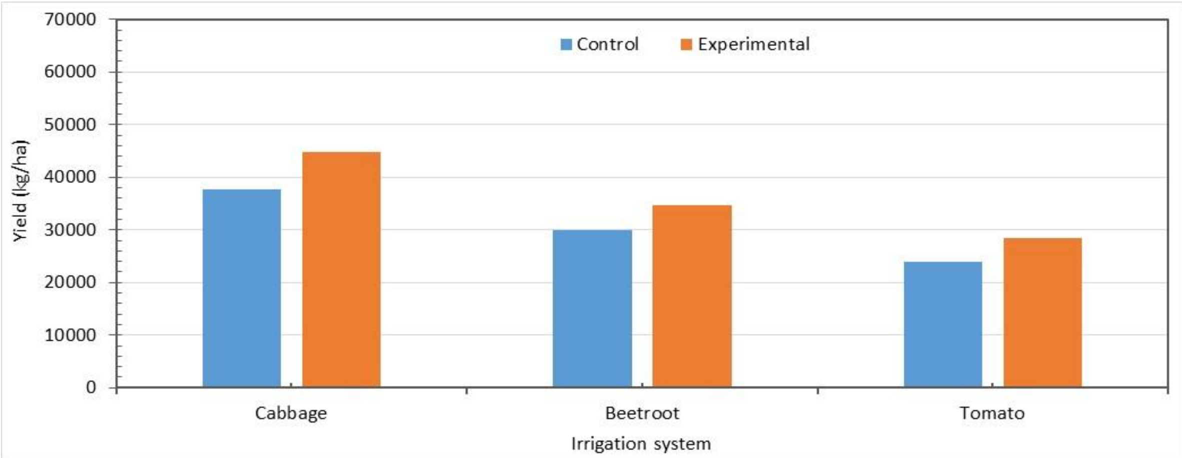

Figure 11b. Yield variation per hectare per crop type

4.6. Irrigation water productivity

Higher overall irrigated water productivity was observed for experimental plots compared to control plots regardless of type of irrigation (Figure 12a). On average the irrigated water productivity increased by 70% under experimental plots from 17 to 28 kg/m^3. This water savings can be used to expand irrigated area to enhance food security. Increase in water productivity was higher for furrow irrigation (319%), while for drip irrigation it was 51%. This lower productivity increase for drip shows that the drip was already performing higher than the furrow prior to introduction of the monitoring tools.

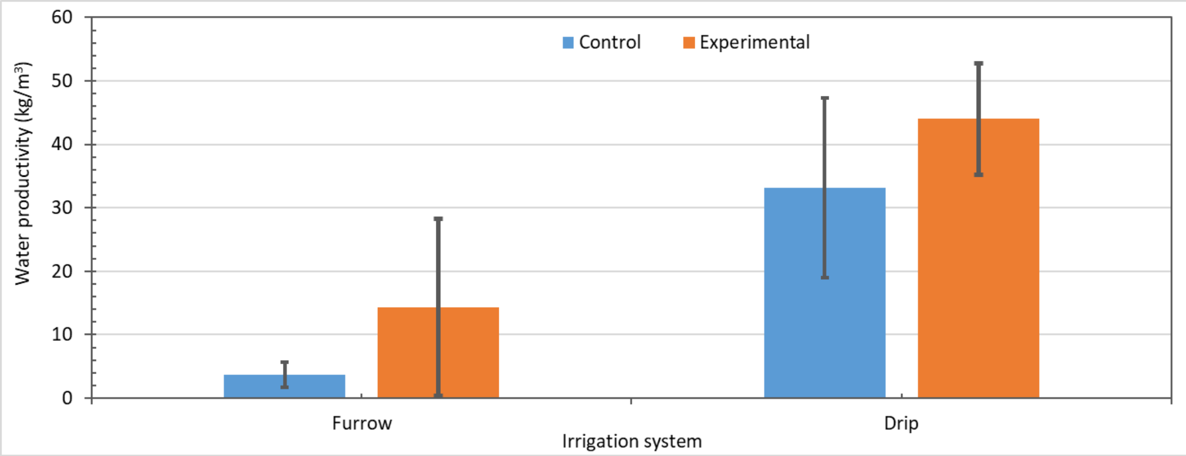

Figure 12a. Overall irrigated water productivity for drip and furrow irrigation system

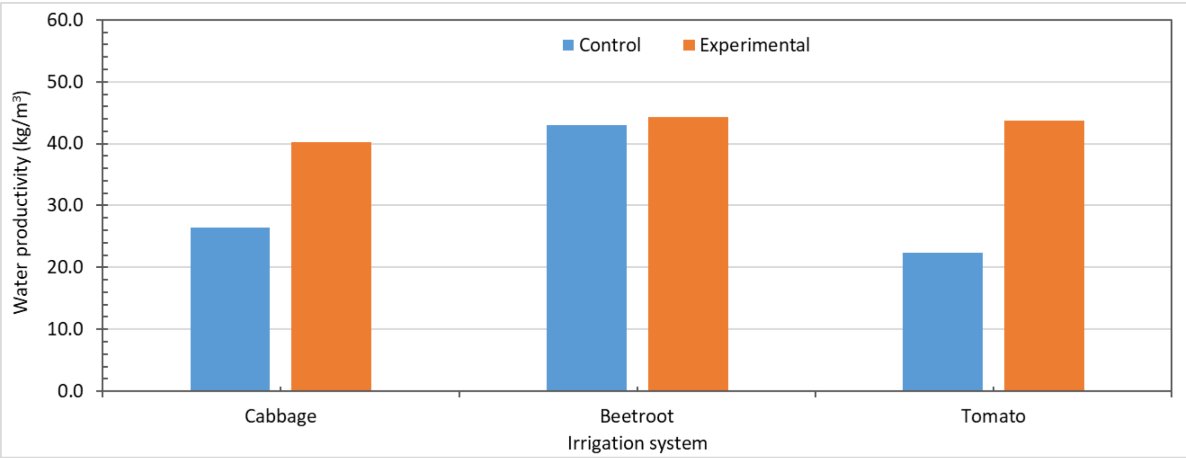

Figure 12b. Average irrigated water productivity for control and experimental plots per crop

4.7. Crop production income

There was significant difference of crop production income (p-value is 0.037) between experimental and control plots in irrigation systems at $p < 0.05$ (Figure 13a). On average the crop production income increased by 36% under experimental plots from ZAR57,949/ha to ZAR80,873/ha, despite market dynamics that resulted in changes in market price and demand. Tomato crop yields had the highest crop production income followed by beetroot, and then cabbage as shown in Figure 13b. Comparison of control and experimental plots under drip irrigation showed no significant difference (p-value is 0.449).

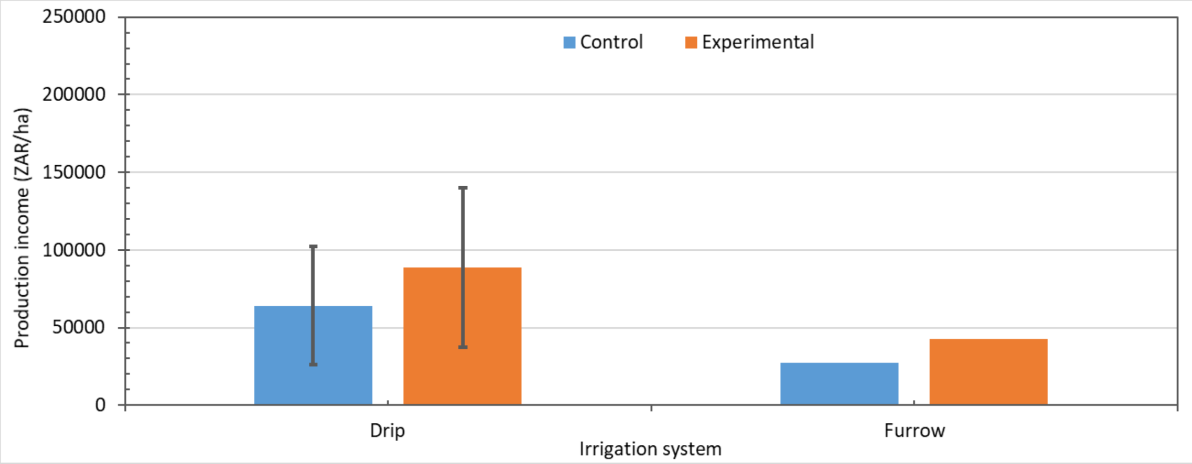

Figure 13a. Production income for drip and furrow irrigation systems.

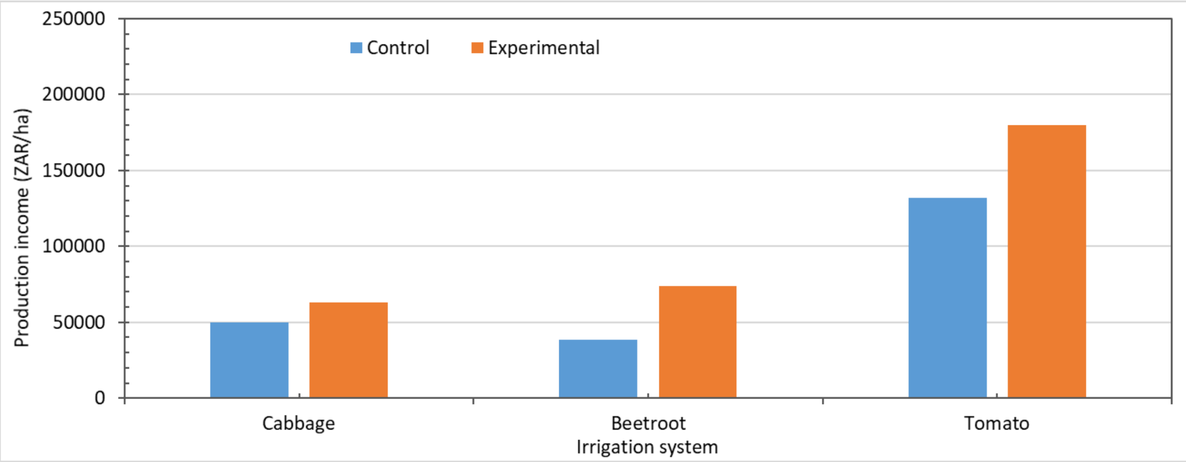

Figure 13b. Production income per crop type

5. Discussion

Significance and importance of this report. This report was an outcome of an extensive, multi-year effort that included identification and selection of irrigation sites in and around the Ramotswa Transboundary Aquifer Area, training of the farmers on installation and interpretation of readings from monitoring tools, installation of the soil-monitoring tools, and data collection and analysis. The findings presented in this report follow from the first major efforts to roll out such tools in smallholder contexts of vegetable production in Africa. Ultimately, the soil-water monitoring tools implemented in smallholder irrigated agricultural were effective in improving existing irrigated water productivity and production, while minimizing adverse environmental impacts of excessive field runoff and nutrient leaching. These findings suggest opportunities for use of the tools in resource-constrained smallholder contexts which may have been overlooked in the past. Indeed, these results are applicable to similar contexts of smallholder irrigation farmers using irrigation water sources from groundwater or from wastewater reuse in semi-arid areas in the Limpopo River Basin and Africa.

Major findings At least five major findings from this report emerged. First, soil-water and nutrient monitoring tools worked, i.e., they were adopted and contributed to a range of positive outcomes. Second, major irrigated water productivity improvement was realized for smallholder irrigation farmers in the RTBAA. Third, there was greater positive impact through use of such tools on furrow irrigation schemes rather than drip irrigation schemes. Fourth, although not significant, yield and income improvement were observed following introduction of such technologies. 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: ***Soil Monitoring Tools worked successfully in the RTBAA*** The monitoring tools, chameleon sensors, electrical conductivity meter and WFD worked to improving the irrigated water productivity, yield and salinity control under relatively low technology smallholder irrigation systems by avoiding over irrigation and the associated adverse environmental impacts of soil erosion and nutrient leaching beyond the root zone into surface or groundwater resources. Smallholder farmers have the capability of using and understanding the soil-water and nutrient monitoring tools to improve their farming practices and reducing the adverse environmental impacts associated with their conventional irrigation practices. Despite scepticism about perceived low technical capacity in the smallholder irrigation farmers, the technology worked and improved the irrigated water productivity and yield. Farmers were able to learn quickly and change their practices when exposed to simple tools that resonate with their objectives of increasing productivity, reducing input costs and overall risk of production failure.

Finding 2: ***Major irrigated water productivity improvement*** Major irrigated water productivity improvement by 70% from 17 to 29kg/m^3 was realized by smallholder irrigation farmers with the use of monitoring tools. Irrigated water productivity increased as more crop yield was produced per unit volume of water put to irrigation and reduced unnecessary irrigation. The reductions in irrigation frequencies per week ranged from 1-2, from 2-4 irrigations per week under normal farmer practices, showing an average reduction of irrigation water use of 40%. These reductions in irrigation frequencies were similar to evidence from Mozambique, Tanzania and Zimbabwe (Stirzaker et al., 2017) that also applied the chameleon sensors and WFD, but to a cereal crop (maize). Studies in other areas reported lower water productivity of 7.8 and 11.9 kg/m^3 for the cabbage and tomato crops, respectively, in Oman, Middle East (Al-Said et al., 2012) and 18 kg/m^3 for tomato in Limpopo, South Africa (Pienaar, 2014). Generally, the use of the WFD has been successful in experimental fields in South Africa (Annandale et al., 2001; Maeko, 2003) and Ghana on cowpea crop (Adimassu et al., 2016).

Finding 3: Greater benefits through use of such tools in furrow irrigation vs. drip. On average the irrigated water productivity improved by 70% following use of soil-water-monitoring tools. For furrow irrigation, water productivity improved by more than 300%, however, for drip it improved by only approximately 50%. Perhaps counterintuitively, this indicates greater water productivity benefits through use of such tools on furrow systems. Similarly, yield and production income showed greater benefits for furrow irrigation systems. For example, yield improved by 72% and 25% for furrow and drip irrigation system, respectively. No study has contrasted furrow and drip irrigation for vegetable crops and under the use of soil-water and nutrient monitoring tools. However, Postel et al. (2001) and Tagar et al. (2012) reported similar yield (50%) and water productivity (150%) improvements for vegetables when comparing use of soil water monitoring tools in drip vs. surface irrigation in India. The finding of this report related to the particular potential for soil water monitoring tools in furrow schemes is therefore new.

Finding 4: Yield improved through use of such technologies Vegetable yield improved by 35% with the use of monitoring tools. Increased yield resulted in improved return on investment from irrigation infrastructure. Economic justification for adapting the monitoring tools in terms of significant yield improvements is adequate to allow vegetable industry to grow in future. In this study like the majority of irrigation studies (Evans and King, 2012), we used only soil-water data for irrigation management to give simple information for a farmer to decide when to irrigate. However, local microclimate and crop genetics that vary within the season, alter crop water needs, and influence the crop yield response (Adeyemi et al., 2017). Ultimately, however, positive changes in yield and income were not significant. Definitive advancement of such factors for as motivation for use of soil-water-monitoring tools in the RTBAA therefore requires further investigation.

Finding 5: There is substantial unrealized potential for use of such tools. Conditions in and around the RTBAA likely represent only a small fraction of the area where conditions of aridity, food insecurity and irrigation coexist in Africa. The relatively low cost of buying and maintaining the monitoring tools – combined with demonstrated benefits such as those elaborated in this report – presents a likely incentive to the broader scale adoption of this technology by farmers provided they receive initial training. Water use regulatory agencies, such as the Departments of Water and Sanitation in Botswana and South Africa may also push to have farmers continuously demonstrate the efficient use of irrigation water to get discounted water charges, where farmers buy water or pay for irrigation water licenses. Ultimately, the benefits of such tools have likely only begun to be felt in Africa.

Closing thought: Benefits of knowledge-sharing and mutual learning Co-learning of researchers with farmers was essential on the use of the monitoring tools. Researchers and farmers learnt from each other through interactions and were flexible to adapt their irrigation scheduling based on the soil-water data observed from the monitoring tools at 0.2m, 0.4m and 0.6m soil depths. Appropriate irrigation scheduling minimizes wasteful losses of irrigation water by percolation beyond salt leaching requirements, reduces surface runoff, evaporation and potential groundwater pollution and maximises crop water transpired. Simple information on soil-water-nutrient patterns from sensors and detectors when compared to farmer’s own experience and intuition provided farmers with further insights on areas where water, salts and nutrient management could be improved in their farms currently and in the next cropping season. The improvements involved application adjustments of water and nutrients.

6. Conclusion

Soil-water monitoring tools in the hands of farmers hold substantial potential to improving sustainable smallholder irrigated agricultural water use, water productivity and production, while minimizing adverse environmental impacts in semi-arid areas of Africa. Significant improvements in crop yield and water savings can be achieved by incorporating the monitoring tools in low technology smallholder irrigation schemes, thereby actualizing the effective use of scarce water resource for food security and rural development. In conclusion, five recommendations are offered:

- ***Expand use of soil water monitoring tools in the RTBAA***. Benefits realized through use of soil water monitoring tools call for expanding their use in the RTBAA. Their use can be advanced through partnering with the local departments of agriculture and any NGOs that are supporting agriculture. Sustainability of their use can be enhanced through continuous farmer training by local agricultural extension officers and availing the monitoring tools at reduced prices to the farmers through the departments of agriculture.

- ***Water productivity improvement, reduced nutrient losses and relative low cost of the acquiring the tools are incentives for the use of the monitoring tools***. The range of benefits of soil water monitoring tools contribute to food security and protection of the environment through reduction in polluted irrigation drainage. The complete monitoring set of tools is also relatively affordable at US$215, but farmers can also separately chose to use nutrient monitoring tools only –WFD, electrical conductivity and nitrate testing strips (US$67) and soil-water monitoring tools only- chameleon sensor and reader (US$147), where resources are limiting.
- ***Special focus should be placed on rolling out the monitoring tools in furrow irrigation systems.*** Furrow may present a better opportunity than drip for application of soil water monitoring tools, due to larger gains in water productivity and other measures. While a larger goal may be to transition to drip irrigation, use of soil water monitoring tools in the context of furrow irrigation schemes may be viewed as an interim measure to save major volumes of water. This roll out should be preceded by adequate and appropriate farmer field training,
- ***Explore opportunities for use of such tools in similar contexts to the RTBAA***. Is may be worthwhile to undertake a mapping exercise to find areas with similar conditions for possible broader scale application of the monitoring tools. For instance, smallholder farming areas with large proportion of surface irrigation systems can be identified and efforts made to reduce irrigation water consumption and nutrient losses by using the monitoring tools.
- ***More research is required in other areas such as sprinkler irrigation system and other vegetable (e.g., high value green and red peppers and watermelons) and cereal crops***. There is need to expand and assess the performance of the monitoring tools under different seasons, climatic conditions and soil types. Farmers, indicated that the tools have greater value during spring (dry hot season) than winter (cold season) when the temperatures are low and evaporation losses are low.

Summing up Policy responses of inclusion of the monitoring tools in water use efficiency programs. To ensure sustainability, the relatively cheap and simple tools of chameleon sensor, electrical conductivity meter and WFD used to assist farmer in making decisions to reduce water use, control salinity and nutrient loss at field level can be included in the agricultural water use efficiency programs of Botswana and South Africa. The outscaling of these monitoring tools should be complemented by regulatory or policy reforms to support farmers trying to reduce their irrigation water demand and improving economic incentives around water (and energy) use and protection. Further, policy responses may include reforms to strengthening farmer organisations including the youths and development of market linkages to enable farmers to get fair prices for profitable irrigation to able to invest in monitoring tools.

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Appendix 1

Table A1. Unit costs for the different instruments

Instrument	Unit costs (ZAR)	Unit costs (US$)	Comment
Wetting front detector (WFD)	283	19.81	One in each field
Electrical conductivity	200	14.00	
Nitrate strips box of 100 strips	480	33.60	Consumable- only need one box per farm per year
Chameleon sensor	600	42.00	One in each field
Chameleon sensor reader	1500	105.00	Only need one per farm and is required to read and upload data on via website: https://via.farm/).
Total	**3, 063**	**214.41**	

Notes. The wetting front detector works with electrical conductivity and the nitrate strips for monitoring excessive irrigation and loss of nutrients, and the total cost is ZAR 963 (US$ 67.41). The chameleon sensor works with the sensor reader for monitoring soil-water in the root zone and excessive irrigation and the total cost is ZAR 2, 100 (US$147). Exchange rate 1 ZAR = 0.07 US$ (Accessed 12 December 2018). https://www.oanda.com/currency/live-exchange-rates/USDZAR/Ac

Photo. Chameleon sensor installation in beetroot crop at Mogobane Irrigation Scheme in Botswana

Photo. Farmer training on draining the wetting front detector and taking readings from a chameleon sensor

Photo. Farmer training on uploading data from chameleon sensor

Photo. Chameleon sensor and wetting front detector installed in beetroot crop at Mogobane Irrigation Scheme in Botswana

Photo. A farmer preparing to take readings from a chameleon sensor for tomato crop at Glen Valley Irrigation Scheme in Botswana

Photo. A youth farmer collecting drainage from a wetting front detector and taking readings from a chameleon sensor and electrical conductivity meter for cabbage crop at Motlhaka Irrigation Scheme in South Africa

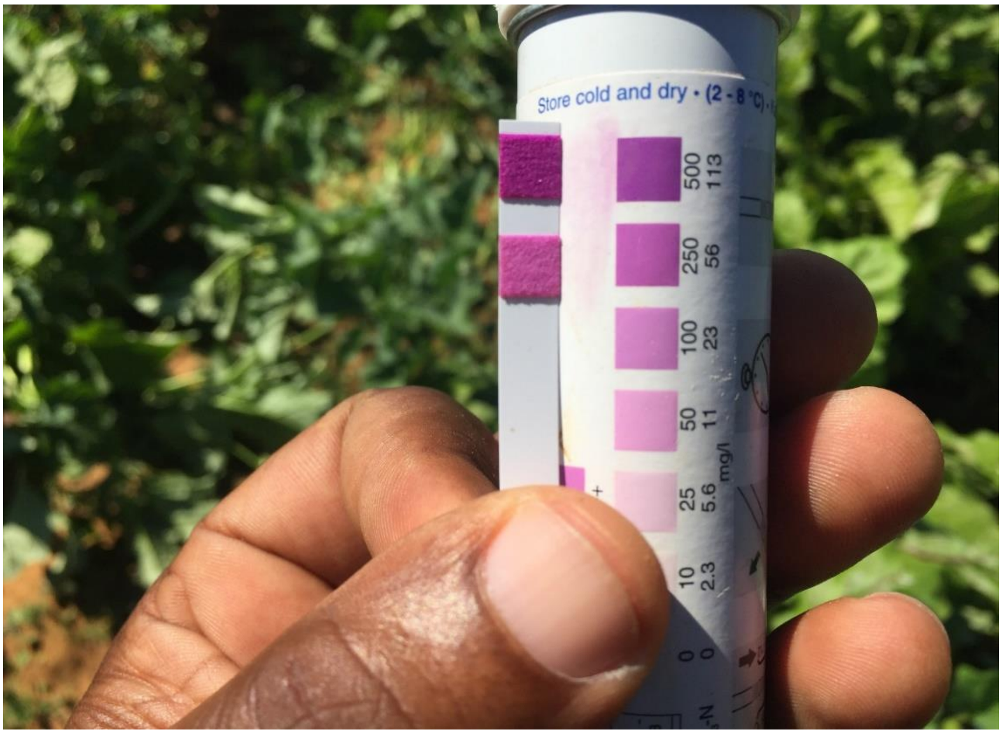

Photo. Assessing the nitrate loss levels from the root zone for a tomato crop in Glen Valley Irrigation Scheme in Botswana

Table A1. Soil nutrient and chemical analysis results from the three irrigation sites in March 2018

Scheme Name	pH (KCl)	P	K	Na	Ca	Mg	Ca	Mg	K	Na	Ca:Mg	(Ca+Mg)/K	Mg:K	Na:K	N-NH4	N-NO3	C Walkley Black	Clay	Silt	Sand
Units	-	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	%	%	%	%	1.5-4.5	10.0-20.0	3.0-4.0	-	mg/kg	mg/kg	%	%	%	%
1 MANDIZHA 16/02/2018	6.16	164	495	146	1107	325	54.83	26.36	12.53	6.29	2.08	6.48	2.10	0.50	0.75	39.43	0.57	20	16	64
2 MAGOBANE 1 (cabbage outside -being harvested now) 16/02/2018	5.67	16	379	78	781	237	54.61	27.13	13.54	4.72	2.01	6.04	2.00	0.35	0.93	27.18	0.77	22	15	63
3 MOGOBANE 2 (cabbage shade) 16/02/2018	6.42	63	294	70	608	241	50.05	32.56	12.39	5.00	1.54	6.67	2.63	0.40	1.43	24.70	0.42	18	17	65
4 DINEO A 16/02/2018	7.30	39	377	159	1253	324	59.23	25.11	9.11	6.55	2.36	9.25	2.75	0.72	1.08	46.08	0.31	10	16	74
5 DINEO B 16/02/2018	6.61	25	668	348	2826	1050	54.44	33.15	6.58	5.82	1.64	13.30	5.04	0.88	0.93	88.58	1.08	38	24	38
6 MOTHLHAKE 16/02/2018	6.55	1	117	20	4053	854	73.30	25.31	1.08	0.31	2.90	91.41	23.47	0.29	1.35	12.58	1.59	24	20	56
Optimum values from literature											1.5-4.5	10.0-20.0	3.0-4.0							