Improving water and nutrient use efficiency of Maize after flooded rice in Bwanje irrigation scheme, Malawi

by

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Declaration

I Nicholas Sichali declare that the mini-dissertation, which I hereby submit for the degree of MSc Water Resources Management at the University of Pretoria, is my own work and has not been submitted by myself or another person for a degree at this or any other institution of higher learning.

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List of abbreviations

ACIAR:	Australian Centre for International Agricultural Research
Anova:	Analysis of variance
BC:	Branch Canal
BVIS:	Bwanje Valley Irrigation Scheme
CS:	Chameleon Sensor
CV:	Coefficient of Variation
CWR:	Crop Water Requirement
CWU:	Crop Water Use
DAES:	Department of Agricultural Extension Services
DARS:	Department of Agricultural Research Services
DoI:	Department of Irrigation
EPA:	Extension Planning Area
ETo:	Reference Evapotranspiration
ETc:	Crop Evapotranspiration
FSSA:	Fertilizer Society of South Africa
FI:	Farmer Irrigation
FIFN:	Farmer Irrigation and Farmer Nutrients
FILN:	Farmer Irrigation and Luxury Nutrients
GAP:	Guide to Agricultural Production
IMP:	Irrigation Master Plan
IR:	Irrigation Requirement
JICA:	Japanese International Cooperation Agency
LSD:	Least Significant Difference
MC:	Main Canal
MGDS:	Malawi Growth and Development Strategy
MK:	Malawi Kwacha

NIPDS:	National Irrigation Policy and Development Strategy
OILN:	Optimum Irrigation and Luxury Nutrients
RCBD:	Randomized Complete Block Design
SE:	Standard Error
SILN:	Strategic Irrigation and Luxury Nutrients
SW:	Soil Water
TC:	Tertiary Canal
TDR:	Time Domain Reflectometry
VIA:	Virtual Irrigation Academy
WFD:	Wetting Front Detector
WUG:	Water User Group

Abstract

Bwanje Valley Irrigation Scheme experiences low maize yields and shortage of water in the winter irrigation season. The scheme is also under-utilized in terms of irrigated area during winter as only 145 ha is cultivated out of a possible 800 ha. This research was carried out to find the best way to utilize water and nutrients in order to improve maize yields, and expand irrigated area planted after flooded rice through optimal use of residual soil water. The experiment had four treatments replicated three times; farmer irrigation and farmer nutrients (FIFN), farmer irrigation and luxury nutrients (FILN), optimum irrigation and luxury nutrients (OILN) and strategic irrigation and luxury nutrients (SILN). Climatic database (Climwat and Cropwat) was used to test the possibility of expanding irrigated area through better residual water utilization by early planting. FIFN received 140 mm after every 21 days (FI) and 104 kg N ha^{-1}, 24 kg P ha^{-1}, 0 kg K ha^{-1} and 17 kg S ha^{-1} (FN). FILN received FI and 180 kg N ha^{-1}, 130 kg P ha^{-1}, 71 kg K ha^{-1} and 5000 kg of Calcitic Lime ha^{-1}(LN). OILN received water based on Chameleon Sensor colours (OI) and LN, while SILN received water only if crops showed signs of water stress (SI) and LN. Results show that FI received more water (488 mm) than OI (255 mm) and SI (235 mm). OILN produced highest yield (5.75 t ha^{-1}) while FIFN produced lowest yield (3.4 t ha^{-1}). FILN yielded 4.7 t ha^{-1} and SILN yielded 4.3 t ha^{-1}. Through a desktop analysis, Cropwat and Climwat indicates that 354 ha would be cultivated utilizing residual soil water by early planting. Therefore; the best way to irrigate is to use Chameleon Sensors and Wetting Front Detectors to schedule irrigation and manage the nutrients respectively, and application of LN increases maize yield.

Key Words: Nutrients, Water, Yields, Area, Chameleon Sensors, Wetting Front Detector

Background Information

Existing Knowledge

This research project was carried out at Bwanje Valley Irrigation Scheme (BVIS) located in Dedza District, Malawi. This irrigation scheme is managed and controlled by farmers with help from Agricultural Extension Development Officers stationed at the scheme and Irrigation Officers from Dedza District Council. BVIS is a gravity fed surface irrigation scheme which abstracts water from the Namikokwe River through a diversion weir. The major crop grown by the scheme is rice, followed by maize and other upland crops. Maize follows summer flooded rice in winter because there is insufficient water to grow flooded rice in this season. BVIS experiences a shortage of water supply and low maize yields in the winter irrigation season. This research was done to improve maize productivity of the scheme through water and nutrient management and expand irrigated area through residual soil water utilization.

Malawi covers an area of 118484 km^2, 21 % of which is water, and 79 % land. Malawi has a rift valley which runs along Lake Malawi towards the eastern side of the country from the northern to southern regions. The country has plateaus and mountains towards the west side of Lake Malawi with altitudes of 750 to 1400 m which run from the northern to the central regions (Johnstone 2011, Veldwisch et al. 2009). In terms of rainfall, the country receives around 725 to 2500 mm from November to April which is called the warm wet season and the dry cool winter season runs from May to August. September and October are hot dry months for the country.

BVIS is in the Mtakataka Extension Planning Area which is in the Dedza District, the central region of Malawi. The Japanese Government, through the Japanese International Co-operation Agency (JICA), rehabilitated and upgraded the small informal scheme to 800 ha for structured irrigation and the first irrigation took place in the early 2000s (Chidanti-Malunga 2009a, Johnstone 2011, Veldwisch et al. 2009). BVIS has 1777 farmers cultivating 590 ha of paddy rice and 210 ha of maize and other upland crops in the rainy season. As a result of water shortages, only 145 ha is planted to maize and other upland crops in the winter irrigation season.

The scheme is divided into three blocks, namely; Branch Canal 1 (BC1), Branch Canal 2 (BC2) and Branch Canal 3 (BC3). BC1 is on the upper side of the scheme, BC2 is in the middle and BC3 is on the lower side of the scheme, towards Lake Malawi. The experiment was carried out on BC1 on an area of 0.09 ha. Soils for BC1 have a sandy clay loam texture. These soils have depths exceeding 150 cm with a soil water holding capacity of 180 mm m^{-1} (DoI 2015). In general, BVIS soils are fluvisols, which are young soils from alluvial and fluvial deposits. Their texture ranges from medium to fine. Based on literature and soil tests results conducted prior to the experiment, pH levels range from 5.6 - 6.3, nitrogen from 0.1 – 0.2 %, phosphorus from 26.5 -74.9 mg kg^{-1}, and potassium from 60.7 – 70.2 mg kg^{-1} (DoI 2015).

In terms of climate, BVIS has an average annual rainfall of 930 mm, 90 % of which falls from November to April. Maximum and minimum annual rainfall totals are 1187 mm and 587 mm respectively. The area has an annual average temperature of 25.1 ^{o}C and monthly average temperatures range from 35 ^{o}C (maximum) in October to 20 ^{o}C (minimum) in June. BVIS also has an average of 8.5 sunshine hours day^{-1}, and the annual wind velocity is 2.3 m s^{-1}. BVIS is located at 14˚16.415ˈ S and 34˚33.503ˈ E with an elevation of 524 m above sea level. Reference evapotranspiration (ETo) for BVIS ranges from 3.80 mm day^{-1} in June, to 6.24 mm day^{-1} in October (Johnstone 2011).

In summer each farmer utilizes 0.45 ha and in winter this is reduced to 0.09 ha if all farmers get a portion of the 145 ha. Irrigation water is supplied to the scheme through a diversion weir and open concrete-lined canals. The river discharge ranges from 0.15 m^3 s^{-1} in October to 5.04 m^3 s^{-1} in February with an average of 2.25 m^3 s^{-1} (NKC 1997). The BVIS headworks intake has a designed discharge of 1.14 m^3 s^{-1}. The main canal (MC) is designed to discharge 0.385 – 1.14 m^3 s^{-1}, branch canals (BC) 0.350 – 0.395 m^3 s^{-1} and tertiary canals (TC) 0.01 – 0.07 m^3 s^{-1}. The designed discharge for the whole scheme is 1.42 l s^{-1} ha^{-1} (JICA 2005).

As determined by the scheme's water users' group, in winter, each farmer receives water for 210 minutes to irrigate 0.09 ha, more or less water is provided depending on the flow in the tertiary canal. In terms of the amount of water irrigated in mm per day after every twenty-one days, BVIS farmers apply on average 140 mm, with each farmer receiving 0.01 m^3 s^{-1} for 210 minutes ((0.01 m^3 s^{-1} * (210*60) s = 126 m^3; thus (126 m^3/900 m^2 * 1000) mm = 140 mm)).

Time taken to irrigate varies with flow rate, such that farmers take less than 210 minutes if they receive more than 0.01 $m^3 s^{-1}$ and more than 210 minutes if they receive less.

At the beginning of the drier winter season, soils in BVIS are very wet because of residual soil water available after flooded rice grown in the wet period. Rice is harvested earliest in April and latest in May. Soils are fluvisols which hold a lot of water and drain slowly. There is no river storage of water during times of surplus and the river declines markedly in winter. The questions are 1) is there an opportunity to expand the limited area irrigated by managing residual water as carefully as possible? 2) can yields be increased on the currently irrigated area? This question is asked because yields are lower than they should be, hence productivity could be improved if limiting factors to production are addressed, even if the area is not expanded.

Each farmer is allocated 0.45 ha for cultivation of rice. Early planting is done in January and late planting is done in February depending on when the rainy season begins in that year. In BVIS, rice takes 150 days to mature physiologically before it is harvested and allowed to dry in the sun. Fields are allowed to drain naturally before harvesting. The soil profile takes 7 to 14 days to drain, such that there is no more standing water in the basins. Harvesting of rice in BVIS begins from early to end of April. The earliest date maize is planted after rice harvest is early May.

According to Kar et al. (2009) the soil profile is very wet soon after rice harvest. Research carried out in India, demonstrated that residual soil water present in the soil profile after rice cultivation can be used to grow maize with minimal irrigation. In that experiment, it was found that key issues in the utilization of this residual soil water are; land preparation methods and time of planting after rice harvest (Kar et al. 2009). Mulched land reduced irrigation requirement by reducing soil water loss through evaporation. Planting soon after rice harvest enables plants to use available residual soil water before it is lost through evaporation and percolation, hence less irrigation water will be needed, while late planting will need more irrigation because the soil profile will have dried up.

Maize is one of the upland crops grown in BVIS with winter irrigation. In general, maize has a rooting depth of 1 m or more (du Plessis 2003) and a physiological maturity period of approximately 131 days depending on the variety, soils, and local weather conditions. In BVIS, a SeedCo cultivar, SC403 is grown in winter. It has a plant height of 2.6 m, and is highly resistant to drought and heat. At 1300 m altitude, SC403 takes 131 days to mature. As per recommendations of the producer of the seed, time to maturity has to be adjusted downwards by 4 days per 100 m decrease in altitude (SeedCo. 2010). So, for BVIS which is at 500 m above sea level, the cultivar takes 99 days to physiologically mature (131 days – ((1300 m – 500 m) / 100 m * 4 days)). This cultivar is preferred over others because of its early maturity and its resistance to drought and heat.

According to SeedCo (2010), depending on rainfall, altitude, soils, water and other agronomic factors, SC403 is likely to yield less than 3 t ha^{-1} with 0-34.5 kg N ha^{-1}, 0-31.5 kg P ha^{-1}, 0 kg K ha^{-1}, 6 kg S ha $^{-1}$ basal dressing and 23-69 kg N ha^{-1} top dressing. It can also yield 8-12 t ha^{-1} with 69-138 kg N, 63-126 kg P ha^{-1}, 0 kg K ha^{-1}, 12-24 kg S ha^{-1} basal dressing and 138-276 kg N ha^{-1} top dressing. In BVIS, each farmer applies 104 kg N ha^{-1}, 35 kg P ha^{-1}, 0 kg K ha^{-1} and 17 kg S ha^{-1} (this is based on a Malawi Government guideline document called Guide to Agricultural Production). SC403 plant density for BVIS is 25 cm between plant stations and 75 cm between rows which gives 53333 plants ha^{-1} and yields on average 3 t ha $^{-1}$. According to FSSA (2007), 180 kg N ha^{-1} applied to maize can potentially yield 8 t ha^{-1} more or less depending on variety and climate. BVIS farmers might be giving insufficient N which could be the cause of low yields. Fertilizer rates applied by BVIS farmers are based on recommendations from soil tests that were carried out a long time ago. These recommendations might not represent the actual status of N, P and K in BVIS soils. The soil has been in use for a long time and crop residues not returned to the soil; hence, nutrients have continuously been mined.

BVIS farmers have no soil water monitoring tools to help them manage irrigation water. Irrigation water management is purely done based on local knowledge and experience. According to Chidanti-Malunga (2009a) and Veldwisch et al. (2009), problems of water shortage and low scheme productivity for BVIS, are caused by poor operation and maintenance of the scheme's infrastructure and lack of ownership by scheme users. Njoloma et al. (2009) also indicated that the irrigated area in winter for BVIS is limited by the low discharge rate of the Namikokwe River, which is the sole water source for the scheme. The limited irrigated area is also caused by poor irrigation water management and lack of maintenance of the scheme’s water infrastructure.

In 2015, the Virtual Irrigation Academy (VIA) project, which is funded by the Australian Centre for International Agricultural Research (ACIAR), introduced soil water monitoring tools to the scheme. Currently, the tools are used by a few selected farmers across the scheme and this research intends to support this intervention by the VIA. These soil water monitoring tools are the Chameleon Sensors (CSs) and Wetting Front Detectors (WFDs). All field data collected from CSs and WFDs monitoring soil water in all project areas is uploaded and can be viewed on Via.Farm (2016a).

The Chameleon Sensor array consists of three porous matric potential sensors with a temperature sensor which determine how wet or dry the soil is at three depths. Sensor arrays are placed at three different depths depending on the root zone depth that needs to be managed. A chameleon field reader is connected to the sensors and displays soil water tension in the sensors. The soil water tension in the sensors is displayed through three colours; blue 0-20 kPa, green 20-50 kPa and red >50 kPa. Red indicates low soil water or plants may be water stressed, while blue indicates enough soil water is available in the soil (or if soil is saturated) and green is the intermediary condition between wet and dry (Via.Farm 2016a)

The Wetting Front Detector consists of a funnel, a long cylindrical tube with an indicator on top of it, a reservoir and a suction tube. They are installed in pairs (shallow and deep). The funnel and reservoir are buried in the ground, and the indicator is visible above ground. When a strong wetting front passes the installation depth, the polystyrene float in the plastic housing rises. The WFD is also used to monitor leaching of nitrates in the soil. A water sample can be collected using a syringe from the reservoir through a suction tube and analyzed using nitrate test strips (Stirzaker et al. 2004, Stirzaker et al. 2010b). Nitrate test strips use colour to denote presence of nitrates when dipped into the extracted water sample. Lighter purple indicates less nitrates present while deeper purple indicates heavy presence of nitrates. When the water sample from the deeper WFD indicates a heavy presence of nitrates, it is an indication that nutrients are being leached from higher up in the soil profile. When this is observed, irrigation needs to be reduced. The most important thing to do is to avoid leaching nitrates deeper into the soil by controlling the amount of irrigation water applied. This ensures nutrients remain within the soil layers which can be accessed by plant roots.

In this experiment, a desktop analysis using Climwat and Cropwat was done to test the effect of planting date on crop water requirement and utilization of residual soil water to potentially expand the area irrigated in BVIS in winter. Climwat is climatic database which is used in combination with Cropwat (computer program) to calculate crop water requirements and irrigation scheduling for various crops for a range of climatological stations worldwide. Analysis for two planting dates, one shortly after rice harvesting and a later planting, was compared. Planting dates were selected based on actual dates used by BVIS farmers. It was not possible to plant twice in this experiment because time was limited.

Research Questions

Below are questions which this research project attempted to answer for BVIS.

- BVIS grows a large area of flooded rice in the wet period which means soils are very wet at the beginning of the drier winter season. These soils hold a lot of water and drain slowly. However, there is no storage of water during times of surplus and river flow declines markedly in winter. The question is; is there perhaps an opportunity to expand the limited area irrigated during winter by managing residual water carefully?
- What are the causes for low maize yields (3 t ha^{-1}) produced by BVIS? Is it caused by the current water (140 mm day^{-1} after every 21 days) and nutrient (104 kg N ha^{-1}) management? Can scheme productivity be improved if limiting factors to production are addressed, even if the irrigated area is not expanded?
- SeedCo and FSSA indicates that is it possible to obtain a yield of 8 t ha^{-1} by applying 180 kg N ha^{-1}, is this attainable for BVIS?
- Would yields be improved if irrigation water and nutrients were managed by CSs and WFDs in BVIS?

Problem Statement

One of the major problems with BVIS is insufficient water for irrigation in the winter season. The Namikokwe River declines markedly in winter. Lack of soil water monitoring devices in the scheme makes utilization of the little available irrigation water difficult. Farmers let the fields dry up before planting winter crops. This perhaps, results in underutilization of residual soil water, which is available soon after the flooded rice harvest.

In this research study, only one planting date was used (the first week of July) and the focus was on the use of simple soil water monitoring tools and nutrient management to improve yield and save irrigation water. However, planting earlier, depending on how wet the soil is after rice harvest, could reduce the irrigation water requirement still further and possibly enable even further expansion of the irrigated area.

The other major problem with BVIS currently is low maize yields. Based on yield information available on Via.farm (2016b), farmers are producing on average 3 t ha^{-1} by appliying 104 kg N ha^{-1}. On the other hand, FSSA (2007), SeedCo (2010) suggest that 104 kg N ha^{-1} should yield 5.3 t ha^{-1} and 180 kg N ha^{-1} should yield 8 t ha^{-1} with proper water and nutrient management.

Problem Justification

In the drier winter season, which is after flooded rice, BVIS fluvisols are wet which is due to available residual soil water. Careful management of this residual soil water could probably enable the expansion of area irrigated. Even if the irrigated area can’t be expanded, yields could still be improved if factors limiting production are addressed.

The lack of soil water monitoring tools at the scheme increases the chances of over-irrigating, leaching of nutrients and crop water stress. This research introduces simple soil water monitoring tools and attempts to determine the best way to irrigate maize, which among other factors, could help improve maize yields and expand the irrigation area for BVIS.

Applying 180 kg N ha^{-1} recommended from literature and proper management of these nutrients with the use of WFDs, could help improve the yield of maize for BVIS. This could be viable for BVIS because currently WFDs are not used and maximum potential maize yields suggested by literature are not attained.

This research is in line with the Malawi Growth and Development Strategy (MGDS), National Irrigation Policy and Development Strategy (NIPDS) and the Irrigation Master Plan (IMP) which emphasize poverty reduction and improvement of household food security of rural livelihoods through increased agricultural productivity.

Hypotheses

1. H_1: Under current farmer practice, maize yields are nutrient limited.

   H_0: Under current farmer practice, maize yields are not nutrient limited.

2. H_1: Under current farmer practice, maize is over irrigated and nutrients are leached.

   H_0: Maize is not over irrigated and nutrients are not leached under current farmer practice.

3. H_1: Better utilization of residual soil water will enable expansion of the irrigated area in winter.

   H_0: Better utilization of residual soil water will not enable expansion of the irrigated area in winter.

Main Objective

The research intends to determine the best way to irrigate without leaching nutrients from the soil and stressing the crop, increase the maize (SC403) yield from 3 t ha^{-1} to at least 7 t ha^{-1} and increasing the irrigated area from 145 ha, which is the designated irrigation area.

Specific Objectives

- To determine if farmers who irrigate 140 mm day^{-1} after every 21 days in BVIS leach nutrients and waste irrigation water.
- To determine if better utilization of residual soil water after rice harvest can facilitate expansion of the area irrigated in winter in BVIS.
- To determine if using Chameleon Sensors to schedule irrigations in BVIS will save irrigation water and improve maize yields.

- To determine if using WFDs to manage nutrients in BVIS will reduce nutrient leaching and improve maize yield in winter.
- To determine if applying 180 kg N ha^{-1} to irrigated winter maize will yield 8 t ha^{-1} in BVIS.

Chapter 1: Literature Review

1.1 Introduction

Bwanje Valley Irrigation Scheme is a gravity fed surface irrigation scheme operated by smallholder farmers. Recently, the scheme has been faced with challenges of insufficient water and low yields in maize, i.e. on average 3 t ha^{-1} (Via.Farm 2016b). Potential causes of these two problems are poor water and nutrient management, and poor field husbandry practices. Irrigation water and nutrients could be better managed with the aid of soil water and nutrient monitoring tools and methods.

Globally, there are several tools and methods used to monitor soil water levels in irrigated and rain fed farming. In Malawi, some of soil water monitoring tools and methods used in irrigated farming are tensiometers, neutron probes, gravimetric methods, and touch-and-feel methods. Tensiometers and neutron probes are mostly used in commercial and private owned farms, while resource limited small-scale irrigation farmers rely heavily on touch-and-feel methods, local knowledge, and experience, because this is all they can afford.

Recently, soil nutrient and water monitoring tools namely Wetting Front Detectors and Chameleon Sensors, were introduced in the scheme. These tools are user friendly and easy to operate (Stirzaker 2005, Stirzaker et al. 2014, Stirzaker et al. 2004, Stirzaker et al. 2010b).

In this research, the best ways to irrigate so that the available water is efficiently used was investigated. Water management, residual soil water utilization, maize production and nutrient management will be highlighted in relation to Bwanje Valley Irrigation Scheme (BVIS) in this chapter.

1.2 Irrigation Water Management

BVIS is a smallholder scheme which is managed by farmers with support from Dedza Agricultural Development Office and Dedza District Irrigation Office. A Water Users' Group (WUG), formed by the farmers within the scheme, is responsible for management of water and land in the whole scheme.

Irrigation water management, at farm level, can be defined as managing the allocation of water and production inputs of an irrigated crop to minimize environmental impacts and increase farm economic returns (Schaible et al. 2006). Managing water in an irrigation scheme reduces water wastage, avoids under irrigation of crops and also increases a scheme's irrigation efficiency. Irrigation efficiency is simply the ratio of amount of water abstracted from the source to that which reaches the plant's roots. Poor irrigation water management in this scheme could be a result of poor operation and maintenance of the scheme's infrastructure, lack of simple soil water monitoring tools to aid farmers in deciding as to when and how much water to irrigate, and poor land and agronomic practices. BVIS farmers have no soil water monitoring tools to assist them in scheduling their irrigation. This could easily result in over irrigation or under irrigation of crops. Over irrigation causes leaching of nutrients and under irrigation causes plant water stress which could reduce yields per unit area.

Irrigation water management can be achieved through use of more efficient irrigation technologies, use of soil water monitoring equipment, computer programs, adoption of less water demanding crop varieties, good land and crop husbandry practices (Ross et al. 1997).

Determined by the scheme's water user group, each farmer of BVIS receives water for 210 minutes to irrigate 0.09 ha depending on the flow in the tertiary canal after every 21 days. In terms of the amount of water irrigated at a time, BVIS farmers irrigate, on average, 140 mm, with each farmer receiving 0.01 $m^3 s^{-1}$ for 210 minutes ((0.01 $m^3 s^{-1}$ * (210*60) s = 126 m^3; thus (126 m^3/900 m^2 * 1000) mm = 140 mm or on average 6.67 mm d^{-1})) (JICA 2005).

According to Clarke et al. (2001) and Smith (1992), computer programs are also used to decide on cropping patterns and schedule irrigations. Cropwat and Climwat are such programs which were specifically developed to aid irrigation water management in irrigation schemes. Cropwat uses the FAO (1992) Penman-Monteith method for calculating reference crop evapotranspiration. The estimates from this program are used in calculating crop water requirements and irrigation scheduling. Cropwat uses Climwat climate and rainfall data files as input. It can then draw and print graphs of input data (cropping pattern, climate) and results (soil moisture deficit and crop water requirements) for analysis and planning in irrigation water management. Complex cropping patterns can be designed for several crops with staggered planting dates.

Climwat offers observed agroclimatic data from over 5000 stations worldwide. This program provides long term monthly mean values of these climatic parameters; mean daily maximum and minimum temperature in ^{o}C, mean relative humidity in %, mean wind speed in km day^{-1}, mean sunshine hours per day, mean solar radiation in MJ/m^{2} day, monthly rainfall in mm month^{-1}, monthly effective rainfall in mm month^{-1} and reference evapotranspiration calculated with the Penman-Monteith method in mm day^{-1}. Data is extracted from single or multiple stations in the format suitable for use in Cropwat (Muñoz et al. 2006, Smith 1993).

Using data from Climwat (from stations near BVIS), Cropwat and data from the current BVIS irrigation regime, a graph can be produced. In the graph, crop water requirement (CWR) and actual irrigation water applied is plotted against time in days.

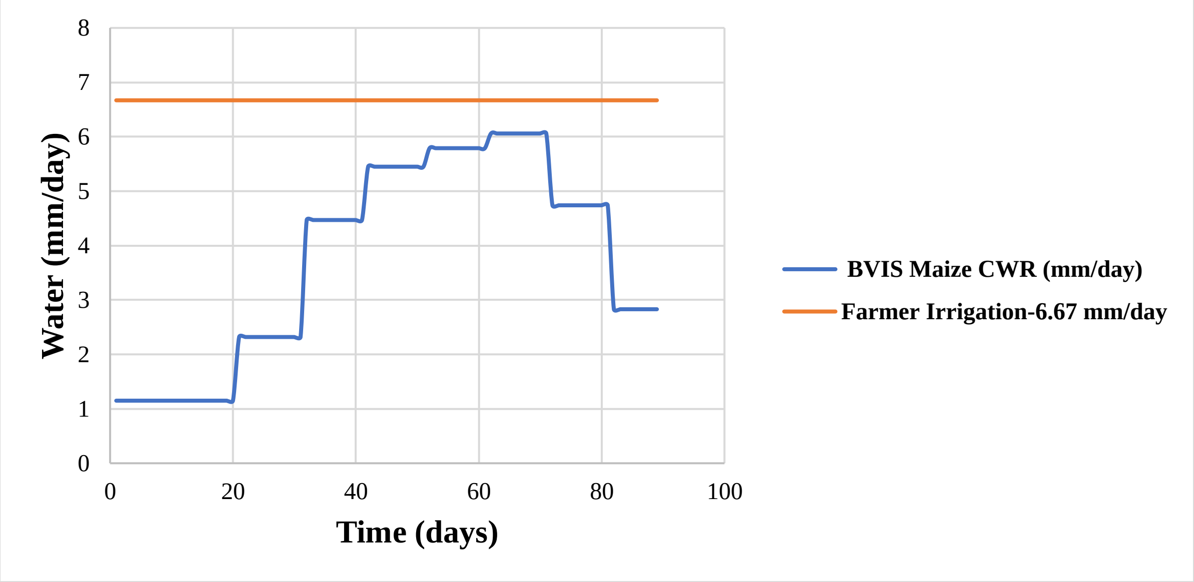


Figure 1. 1: Climwat and Cropwat data; BVIS maize crop water use and irrigation for BVIS (Muñoz et al. 2006, Smith 1993).

Figure 1.1 presents the irrigation rate applied by farmers and calculated CWR. It is evident that farmers over irrigate their maize.

1.3 Soil water monitoring tools

In BVIS, currently, farmers have no soil water monitoring tools. They use the touch-and-feel method, local knowledge, and experience when scheduling their irrigation. Globally, there are several methods and tools which are used to schedule irrigation in order to improve farm productivity in terms of water use, yields and economic returns. Farmers in BVIS use the touch-and-feel method, while Cropwat, Climwat and the gravimetric method are used in other irrigation schemes in the country. Private commercial farms use tensiometers and neutron probes. WFDs and CSs are currently being used by a few selected farmers in BVIS under the supervision of the VIA project. According to Stirzaker et al. (2014) and Stirzaker et al. (2004), these tools are convenient in terms of use, operation and maintenance for small-scale irrigation farmers with a low level of education and income.

Neutron Probe

The neutron probe was introduced in the 1950s with the purpose of having more accurate soil water records (Evett et al. 1995). It comprises a nuclear source which is suspended by a cable with a protective housing. The neutron probe measures the soil water content as the nuclear source is lowered into an installed access tube (Charlesworth 2005a). It utilizes radioactive americium (an alpha particle emitter) to measure volumetric water content. Any country which uses the neutron probe is obliged by law to obtain a license and provide training to users and adhere to safety regulations.

The neutron probe was found to be precise and satisfactory and proved to be beneficial for soil water measurements (Evett et al. 1995). Neutron probes have the capability to determine soil water content at over 80% accuracy. In the measurement of temporal changes in volumetric water content, the neutron probe is reliable, because this is not affected by the access tube-air gap (Cayci et al. 2009, Grant et al. 2004). However, the neutron probe has limitations, such as being restrictive in its utilization due to the radioactive source. When soil water is measured close to the soil surface, the neutron probe proves to be inaccurate due to neutrons escaping from the soil into the atmosphere without being detected, hence it is not recommended to estimate ET even if calibrated (Evett 2000). The amount of water applied by farmers to crops mismatches the amount of water which is effectively and efficiently used by the crop (Stirzaker 2003). This is because farmers do not utilize the device systematically (Stirzaker 1999). It has also been noted that most farmers are unable to install, calibrate and interpret data correctly from the device (Charlesworth 2005a, Peters et al. 2013).

Time Domain Reflectometry and Capacitance Probes

Non-nuclear soil water devices such as Time Domain Reflectometry (TDR) and capacitance sensors have been developed. These devices use the electromagnetic field that is generated to measure the dielectric property of the soil which is translated into soil water content (Charlesworth 2005a, Noborio 2001).

Table 1.1 highlights the advantages and disadvantages of different soil water monitoring devices.

Table 1. 1: Advantages and disadvantages of the most important soil water monitoring devices (Peters et al. 2013)

	Sensor type	**Advantages**	**Disadvantages**
Soil water content	**Neutron probe**	Accurate, Repeatable, Samples a relatively large area.	Government requires paper work and regulations, cannot be left in the field due to radiation issues.
	Time Domain Reflectometry	Less expensive, easy to log data.	Samples small area.
	Capacitance sensors (Sentek EnviroSCAN, Diviner 2000)	Easy to set up, to log or transmit data	Highly affected by the soil condition next to the sensor, high variability, more expensive.
Soil water tension	**Tensiometer**	Less expensive	Requires frequent maintenance, affected by freezing, can’t measure tension greater than 80 kPa

Tensiometers

In the 1930s the tensiometer was introduced as an instrument for soil water monitoring. The tensiometer comprises a porous ceramic cup, sealed water filled plastic tube and a vacuum gauge. The porous ceramic cup gets buried in the soil and permits the movement of water in and out between the water filled tensiometer and the soil. The pressure created during the movement of water is equal to soil suction and is recorded by the vacuum gauge. This information is used to determine when to irrigate (Charlesworth 2005a).

The tensiometer is less expensive, can easily be understood and no calibration is required (Stirzaker 2003).

Smajstrla et al. (1996) carried out a study on water use efficiency using tensiometers in tomatoes in Florida, and found that water use efficiency improves from 50% - 60%. Increase in tomato yields, reduction of nutrient leaching through the use of tensiometers was realized in a study conducted by Li et al. (1998).

In trials conducted in Australia, tensiometers did not give the expected results because field soil water conditions were not constant in the season (Charlesworth 2000). In another study conducted in citrus, the tensiometer provided unrealistic data because of entrapped air and growth of organics on the ceramic cup. Unless the tensiometer is recalibrated, realistic data cannot be realized (Smajstrla et al. 1986). Charlesworth noted that tensiometers cannot record soil water suction of more than 75 kPa due to air that enters the ceramic tip (Charlesworth 2005a).

Wetting Front Detectors

This instrument has a filter, a funnel, a float and an indicator. The indicator is above the ground while the funnel is buried in the soil close to the root zone of the planted crop. This device works on the flow line convergence principle. When a strong wetting front passes the installation depth, the polystyrene float in the plastic housing rises. Soil water will flow through the filter into the small reservoir in the funnel that activates the float (Stirzaker et al. 2010a). It is also described as an instrument that alerts an irrigator when infiltrating water has passed a given depth. When used as an irrigation scheduling tool, WFDs are always installed in pairs (shallow and deep) (Stirzaker 2003).

The base of the WFD retains a sample of water which is collected using a syringe via the extraction tube. This soil solution can be analyzed for salts and nutrients. Nitrate test strips use colour to denote presence of nitrates when dipped into the extracted water sample. Figure 1.2 shows nitrate testing using nitrate strips.

Figure 1. 2: Nitrate testing of soil solution extracted from a WFD (Via.farm 2016a)

In dry soils, the WFD will take time to respond because water will move slowly, filling the soil pores as it infiltrates down, hence longer irrigation periods are needed. For wet soils, the WFD response will need short irrigation periods (Stirzaker et al. 2004). WFDs can be used to schedule irrigation and they were built to fill a perceived gap of “simplicity and user friendliness” of soil water monitoring tools in irrigated agriculture (Stirzaker et al. 2010a).

WFDs are installed in pairs, thus one is placed at a shallow depth at the top of the root zone of the crop and other one is placed deeper towards the bottom of the root zone of the crop. Heavy presence of nitrates from a soil solution from a deeper WFD indicates leaching of nutrients from higher up in the profile. Under irrigation will be indicated when none of the instruments are activated and if both instruments are activated regularly it is an indication that the crop is being over irrigated. Normally intermediate situations are preferred (Stirzaker et al. 2004).

According to Stirzaker et al. (2004), WFDs have sensitivity levels of 2 kPa or 20 cm of suction. Two processes determine the sensitivity of a detector. These are capillary action which moves water out from the funnel and convergence which moves water into the funnel. If convergence is more than capillary action, then there will be more free water in the funnel which will activate a float. Therefore, the funnel diameter and the rim depth to the filter determines the sensitivity of the detector. However, in deeper soils where there is low convergence and low flux, a WFD may not be suitable for detecting a wetting front (Stirzaker et al. 2004).

Successful functionality of WFDs depend on the correct placement depth which should match the irrigation system and strategy (Stirzaker et al. 2010a).

Stirzaker (2005) indicated that the WFD has some limitations. The WFD only tells the irrigator how well the previous irrigation went and not when to start the next irrigation. It is up to the farmer to decide when to irrigate and the length of the next irrigation. Another limitation with the WFD is the inability to detect fronts weaker than 2 or 3kPa. This could lead to over irrigation because significant amounts of water infiltrating down may not be detected by the instrument such that activation will not happen. Stirzaker et al. (2004) reported that farmers indicated the difficulty in installation in terms of determining the right depth of placement, they also complained of soil disturbance during the installation. It was also noted that the WFD performed better with drip irrigation than center pivot and furrow irrigation methods.

Chameleon Sensors

A Chameleon Sensor is a simple soil water sensor with a reader that measures soil water tension at three depths in the soil profile. The reader displays the status of water in the soil through colours. A blue colour for wet soil, red for dry soil and green for intermediate soil water status. The sensors are buried in the soil and the reader is visible on the ground. African co-workers named the sensor "The Chameleon" because it changes colour to reflect its surroundings (Stirzaker et al. 2014). Generally, there are agreed ranges of soil tensions during which irrigation should take place. Table 1.2 shows when water must be applied to crops based on the colours shown by the Chameleon reader

Table 1. 2: Suggested ranges for irrigation for vegetable crops (Stirzaker et al. 2014).

Colour	Water level (Meaning)	Irrigate in this range (or before)	VEGETABLE CROP
Blue	Wet soil	20-30 kPa	Broccoli, Celery, Lettuce, Onion
Green	Moist soil	30-45 kPa	Beans, Cabbage, Carrot, Capsicum, Corn, Cucumber, Eggplant, Melons, Potato, Tomato
Red	Dry soil	>60 kPa	Beet, Peas, Sweet potato, Pumpkin

According to Stirzaker et al. (2014), currently there are no instruments for developing countries that can simplify water measurement to the point that it can widely be used. Stirzaker says that by taking a novel sensor idea and coupling it to a visual colour display data would reduce difficulties faced by farmers to monitor soil water tension.

Through field trials, the Chameleon Sensor has been found to be just as accurate as other scientifically accepted soil water monitoring devices like tensiometers. In the report by Stirzaker et al. (2014), it was shown that trial results for Chameleon Sensors and tensiometers carried out on tomatoes for 98 days under the same cropping conditions, were not different.

Chameleon Sensors are being used and tested in the VIA project currently being implemented in Malawi, Tanzania and South Africa. This project is funded by ACIAR. Preliminary results indicate a positive change in behaviour of farmers on how to manage their irrigation water. Chameleon Sensors are also being used in other countries in southern Africa, such as Mozambique and Zimbabwe.

According to Stirzaker et al. (2014), the Chameleon has removed the problem of interpretation by having sensors which measure soil tension, not water content. Installation complications as experienced with other devices have been reduced by making sure that Chameleon performs well as long as its sensors are in contact with the soil. By using a colour diode (Blue, Green and Red) to indicate water tension in soil, the CS has removed the complications of interpreting and translating units by the farmer. Using a colour diode to monitor water tension in the soil would also simplify the complexity imposed to interpret and access the data for farmers with low level of education.

1.4 Soil Water Monitoring Methods

Gravimetric

The gravimetric soil water monitoring method involves obtaining a soil sample, weighing it, oven drying then reweighing it. The difference in mass is taken to be the mass of soil water which is then expressed as a percentage of the oven dry mass of the soil. Soil samples are collected using soil augers, core samplers or aluminum tins. The collected soil samples are oven dried at 100 to 110 ^{o}C for 24 hours repeatedly until there is no difference in the oven dry weight of the soil (Black et al. 1965, Reynolds 1970a).

One of the limitations with gravimetric soil water measurement is that its time consuming to obtain results compared to other methods like tensiometers and neutron probes. This is because it requires samples to be collected from the field, then oven dried for 24 hours repeatedly, and calculations have to be done afterwards to determine the percentage of water available in the soil. This method is also labour demanding, but on the other hand, gravimetric soil water determination is the oldest, most reliable and widely used method in determining soil water content. (Charlesworth 2005b, Reynolds 1970b)

In BVIS, because there is no equipment to use this method in scheduling irrigation, hence it is not used. If farmers are to use it, it means soil samples have to be taken to a research station which is about 250 km away from the scheme. The low level of education in farmers has also makes it more difficult for the scheme users to become familiarized with the technique. This provides an opportunity for the introduction of new, simple and user-friendly soil water monitoring tools.

Feel-and-Appearance Method

According to Klocke et al. (1998), the feel-and-appearance method is one of the methods used to schedule irrigation by farmers. It is used to monitor soil water and decide when and how much to irrigate. Feel-and-appearance involves obtaining a soil sample at an intended depth using a soil auger, shovel or hoe. The collected soil sample is then squeezed several times in the hand to form an irregularly shaped ball or between thumb and fore finger to form a ribbon. The resistance of the ball or ribbon to disintegrate when bounced indicates how much water is available in the soil. Soil balls or ribbons with less soil water disintegrate easily, while those with a higher soil water content will not. This method is easy to use and cheap.

In BVIS, most farmers use the feel-and-appearance method in scheduling their irrigation. They use this method in combination with local knowledge and experience. The only shortcoming of this method is that it has low accuracy levels. This makes the method unreliable, hence farmers would still over irrigate or under irrigate when using this method to schedule their irrigation.

1.5 Residual Soil Water Utilization

According to Kar et al. (2009), research in India, demonstrated that residual soil water present in the soil profile after rice cultivation can be used to grow maize with minimal irrigation. In their experiment, it was found that the key issues in utilization of this residual moisture are; land preparation methods, time of planting after rice harvest and method of planting. Reduced tillage and planting soon after rice harvest produced better results than zero and conventional tillage.

Results from BVIS farmer plots observed on Via.farm (2016b) indicate that the soil profile is wet soon after rice harvest. Current planting dates for BVIS, show that farmers do not plant soon after rice harvest, they wait until the soil dries down somewhat.

1.6 Surface Irrigation System

A surface irrigation system is when water is conveyed from the source to the field through unlined or lined open channels or low head pipelines. This system is cheaper than overhead (sprinkler) and subsurface irrigation systems in terms of capital costs. However, surface irrigation systems are deemed to be more labour intensive than overhead and subsurface irrigation systems. Surface irrigation systems are suited to lands with uniform terrain and slopes less than 3%. Surface irrigation systems require soils with low to moderate infiltration capacities (Booher 1974).

Surface irrigation systems consist of three primary methods namely; furrow, border, and basin irrigation methods. In basin irrigation, water is flooded into basins until it ponds and the surface gets waterlogged. Fields under this method are graded and divided into units surrounded by small dikes. The method is suited to soils with moderate to low infiltration capacities and smooth, gentle sloping lands. The basin irrigation method is not recommended for crops sensitive to wet soil conditions and soils that crust when flooded (Bishop et al. 1967, DoI 2015). This method is used in BVIS in summer when they grow rice on 800 ha. Basins are 30 m by 30 m in size. In summer, water is diverted from the Namikokwe River using a weir, then flooded into field basins. During this period, water is not a problem for the scheme because there is sufficient discharge volume from the river.

In the border irrigation method, parallel earth ridges, called borders, are used to guide a sheet of flowing water through a field. A border strip, which is the area between borders, may vary from 3 to 30 m in width and 100 to 800 m in length. Just like in basin irrigation, crops sensitive to wet soil conditions are not recommended under this irrigation method (Walker et al. 1987).

With the furrow irrigation method, small channels called furrows are constructed across the field slope that carry running water. Water is diverted from field canals into furrows through siphons or open ditches. This method is suited to fine textured, slowly permeable soils on relatively flat land. Furrow irrigation methods suit crops which are sensitive to waterlogged conditions. Furrow irrigated crops are planted on ridges, just next to the furrow (Bishop et al. 1967, Booher 1974, Walker et al. 1987). In BVIS, farmers use furrow irrigation method in winter when they grow upland crops e.g. maize and beans. Water shortage is one of the major problems faced by the scheme during the winter season.

According to Johnstone (2011), water shortage will continue to be a problem for BVIS because it utilizes a common water resource (Namikokwe River) which is part of the larger ecosystem. The ecosystem determines the amount of water available for irrigation in BVIS. The scheme is vulnerable to changing water and weather conditions in the absence of interventions like dam construction and in-scheme water storage reservoirs. Currently, a dam is under construction in the upper section of the Namikokwe River, with funding from the European Development Fund, to try to alleviate the water shortage caused by decreased river flow discharge in the winter irrigation season.

According to Chidanti-Malunga (2009a) and Veldwisch et al. (2009), problems of water shortage and low scheme productivity for BVIS, are caused by poor operation and maintenance of the scheme’s infrastructure and lack of ownership by the scheme users. This is a result of a lack of participatory approaches and local community involvement in the implementation of rehabilitation works done by donors. Farmers were hardly involved in the development and rehabilitation process of the scheme, which resulted in a lack of ownership and under developed capacity of farmers to effectively manage and operate the scheme.

Njoloma et al. (2009) also indicates that the size of irrigated area in winter for BVIS is limited because of low discharge volume of the Namikokwe River, which is the sole water source for the scheme. The limited irrigated area is also caused by poor irrigation water management and lack of maintenance of the scheme’s water infrastructure. The area under irrigation in winter could be increased if water storage reservoirs are constructed and proper irrigation water management is carried out.

1.7 Parshall Flume

The Parshall Flume is a hydraulic structure used to measure the flow of water in open channels. This device was originally developed to measure water flows for irrigation/water rights, but with time, its use was expanded to measure discharge in dam seepage, industrial effluent, mine discharge, sanitary sewage, storm water, and cooling discharge (Parshall 1950, Robinson 1957). It was developed by Dr. Ralph l. Parshall in 1915 for use in irrigation/water rights at the United States Soil Conservation Services. Under laboratory conditions, the accuracy of the Parshall Flume has been found to be +/-2%, while under field conditions, accuracy has been found to be +/-5%, (when factors like installation, approach, flow and dimensional tolerance are considered) (Robinson 1957).

With the Parshall Flume, the point of measurement for upstream flows is H_a and for submerged conditions, it is H_b. Several water level depth measurements at point H_a are recorded and then averaged. This averaged value is then used in the equation, $Q = KH_a^n$, to calculate discharge in $m^3\ s^{-1}$. In the equation, Q is the free flow rate in $m^3\ s^{-1}$, K is the flume discharge constant (varies with flume size), H_a is the depth at point of measurement in metres, and n is the discharge exponent (depends on flume size) (Robinson 1957). K and n values can be obtained from empirical tables depending on flume throat size. Table 1.3 shows n and K values depending on the flume size.

Table 1. 3: Parshall Flume free flow discharge K and n values. Adapted from (Parshall 1950)

Throat Width (cm)	K ($m^3\ s^{-1}$)	n
2.54	0.0479	1.55
5.08	0.0959	1.55
7.62	0.141	1.55
15.24	0.264	1.58
22.86	0.393	1.53

30.48	0.624	1.522
45.72	0.887	1.538
60.96	1.135	1.55
91.44	1.612	1.566
121.92	2.062	1.578
152.4	2.5	1.587
182.88	2.919	1.595
213.36	3.337	1.601
243.84	3.736	1.601
304.8	4.709	1.6
365.76	5.590	1.6
457.2	6.912	1.6
609.6	9.117	1.6
762	11.32	1.6
914.4	13.53	1.6
1219.2	17.94	1.6
1524	22.35	1.6

In table 1.3, K and n values are provided for calculation of discharge Q in m^3 s^{-1}, using the formula highlighted above. K and n values should be selected based on the flume throat width (cm) being used.

In BVIS, this device is not used by the farmers, but was used on research trials for the duration of the experiment. It was used to measure the amount of water applied to treatments whenever they were irrigated. This enabled researchers to record the amount of water in m^3 irrigated to maize for the whole growing season. This data made it possible to determine and compare the amount of water used by all treatments. This was necessary, because one of the objectives of this research was to find the best ways to irrigate maize while minimizing water wastage without stressing the crop and compromising yields.

1.8 Maize

Maize is a grain crop produced under diverse and wide ranging of environmental conditions. Maize has an adventitious root system which can reach more than 1 m in depth depending on the soil conditions. The optimum germination temperature is between 20 ^oC and 30 ^oC, while the soil water content should be above 60 % of the soil water holding capacity. The minimum temperature for germination is 10 ^oC and at 20 ^oC, maize should take five to six days to emerge. Depending on the maize cultivar, the crop takes around 90 to 140 days to mature (FSSA 2007, du Plessis 2003).

In terms of water, maize requires 350 to 600 mm of water per season. Every millimeter of water used, produces 10 to 16 kg of grain and a yield of 3150 kg ha^{-1} requires approximately 350 to 450 mm of water per season. In the absence of soil water stress, each plant uses 250 l of water per growing season, depending on the particular climate and cultivar, assuming optimal management (du Plessis 2003). In terms of nutrients, at maturity, and again depending on the cultivar, generally, a single maize plant uses 8.7 g of nitrogen, 5.1 g of phosphorus and 4.0 g of potassium. Each ton of grain produced, removes 15 to 18 kg of nitrogen, 2.5 to 3 kg of phosphorus, and 3 to 4 kg of potassium from the soil. Usually, in maize, nitrogen and potassium uptake reaches at peak two weeks prior to flowering while phosphorus uptake is a maximum at flowering (Benjamin et al. 1997, FSSA 2007, du Plessis 2003, SeedCo 2010).

Maize is one of the upland crops grown in BVIS under irrigation. Maize has a physiological maturity period greater than 90 days depending on the variety, soils, and local weather conditions. In BVIS, a SeedCo cultivar, SC403, is grown under winter irrigation. It has a plant height of 2.6 m, is highly resistant to drought and heat, is slow drying and takes 131 days to physiologically mature at 1300 m altitude. SC403 in BVIS (500 m altitude) takes 99 days to physiologically mature.

According to SeedCo (2010), depending on rainfall, altitude, soils, water and other agronomic factors, SC403 will yield less than 3 t ha^{-1} with 0-34.5 kg N ha^{-1}, 0-31.5 kg P ha^{-1}, 0 kg K ha^{-1}, 6 kg S ha^{-1} basal dressing and 23-69 kg N ha^{-1} top dressing. It can also yield 8-12 t ha^{-1} with 69-138 kg N ha^{-1}, 63-126 kg P ha^{-1}, 0 kg K ha^{-1}, 12-24 kg S ha^{-1} basal dressing and 138-276kg N ha^{-1} (46 % N) top dressing. In BVIS, 104 kg N ha^{-1}, 35 kg P ha^{-1}, 0 kg K ha^{-1} and 17 kg S ha^{-1}is applied by each farmer. Below is a graph which has been produced using data from the Fertilizer Society of South Africa (FSSA) handbook. Figure 1.3 shows the relationship between the amount of nitrogen in kg ha^{-1} and potential yield for maize in t ha^{-1}. FSSA also emphasize that factors like leaching, denitrification, soil nutrient status, weed control, plant population and crop removal could affect nitrogen requirement, and this must therefore be considered when using the fertilizer handbook.

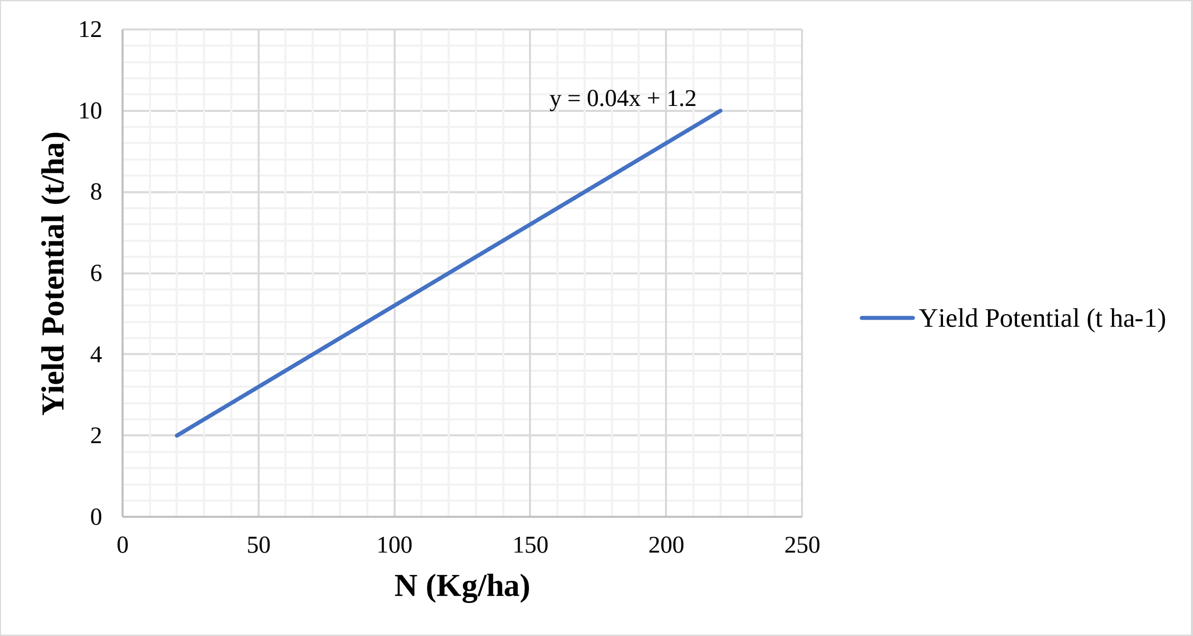


Figure 1. 3: Relationship between nitrogen and potential maize yield per ha (FSSA 2007).

According to the FSSA (2007), as indicated earlier, when using these guidelines, factors, which could influence nitrogen requirement, should be considered. These factors are denitrification (occurs when there is limited supply of oxygen in the soil), leaching (loss of nitrates from the root zone after excessive rain or irrigation), symbiotic N-fixation (the capacity of legumes to convert atmospheric nitrogen into a usable form through the action of roots and micro-organisms) and N-negative period (when large amounts of organic matter are incorporated into the soil). Consideration of these factors will determine whether to add more nitrogen to the soil than what these guidelines recommend or not.

Under similar agronomic practices and factors, using this graph, 104 kg N ha^{-1} applied by BVIS should yield 4.8 t ha^{-1}, but instead farmers produce on average 3 t ha^{-1}. This research intends addressing this problem.

Chapter 2: Materials and Methods

2.1 Site Location

The research was conducted at Bwanje Valley Irrigation Scheme (BVIS) which is located in the Dedza District of Malawi. The research period was from 24th July 2017 to 24th November 2017. The scheme is located near Lake Malawi in the Bwanje Rift Valley, Mtakataka Extension Planning Area (EPA), Traditional Authority Kachindamoto. In terms of co-ordinates, the scheme is located at 14˚16.415' S and 34˚33.503' E with an elevation of 524 m above sea level. Figure 2.1 shows the location of BVIS on a map of Malawi.

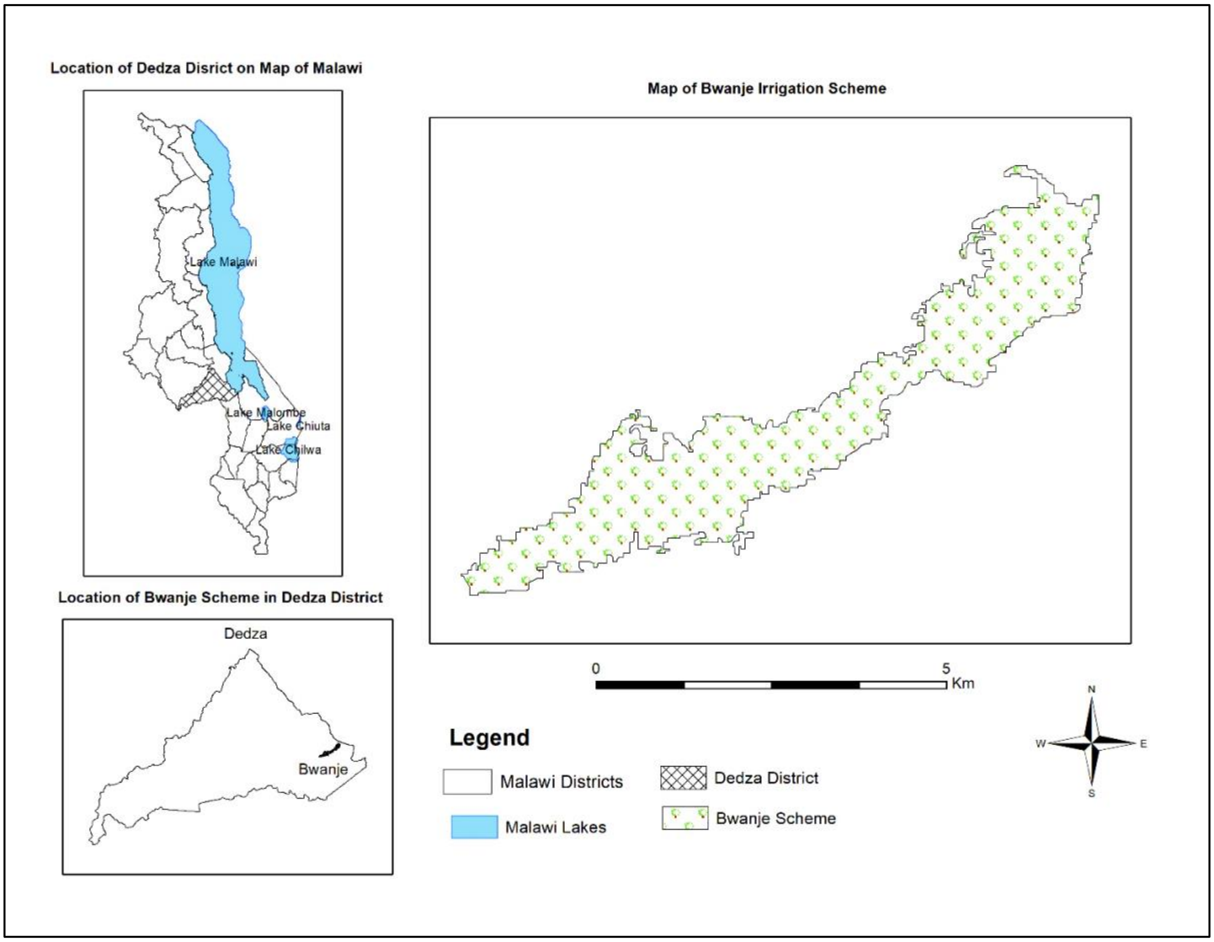


Figure 2. 1: Location of Bwanje Valley Irrigation Scheme

2.2 Soil sampling

Soil sampling was done in Branch Canal 1 (BC1), Branch Canal 2 (BC2) and Branch Canal 3 (BC3). Using core samplers, soil samples were taken from top soil (0-20 cm) and subsoil (20-60 cm) from all three blocks of the scheme. In total, 24 soil samples were taken and sent to Chitedze Research Agricultural Research Station in Lilongwe for analysis. Analysis was done for pH, organic carbon, organic matter, nitrogen, phosphorus, potassium, soil texture and bulk density.

2.3 Experimental Treatments

The research trial had four treatments. The first was called Farmer Irrigation and Farmer Nutrients (FIFN). Under FIFN, amount of water and nutrients applied was the same as that applied by farmers in the scheme. FIFN received 140 mm after every 21 days, 104 kg N ha^{-1}, 24 kg P ha^{-1}, 0 kg K ha^{-1} and 17 kg S ha^{-1}.

The second treatment was called Farmer Irrigation and Luxury Nutrients (FILN). In this treatment, 140 mm after every 21 days was applied, the same as farmer irrigation, as well as 180 kg N ha^{-1}, 130 kg P ha^{-1}, 71 kg K ha^{-1} and 5000 kg of Calcitic Lime ha^{-1} and this combination of nutrients was termed luxury nutrients. Soil liming rate of 5000 kg limestone ha^{-1} was done based on the soil tests results and recommendations by the Ministry of Agriculture, Irrigation and Water Development through the Department of Agricultural Research Services (DARS).

The third treatment was called Optimum Irrigation and Luxury Nutrients (OILN). This treatment was irrigated only when Chameleon colours on the reader showed green at 20 and 40 cm depth, or red at 20 and green at 40 cm depth. A minimum of 25 mm of water was applied so that the Chameleon reader colours at both, 20 and 40 cm depths changed to blue and a little more was added later. This treatment also received 180 kg N ha^{-1}, 130 kg P ha^{-1}, 71 kg K ha^{-1} and 5000 kg of Calcitic Lime ha^{-1}.

The fourth treatment was called Strategic Irrigation and Luxury Nutrients (SILN). This treatment was designed to stress the crops as much as possible. Water was applied only when plants started showing clear physical signs of being water stressed i.e. curling of the leaves and flaccidity, and when the Chameleon colours on the reader showed red at 20 and 40 cm and green at 60 cm depths. A minimum of 20 mm of water was applied so that the Chameleon reader colours at all three depths (20, 40 and 60 cm) changed to blue and a little more was added later. This treatment also received 180 kg N ha^{-1}, 130 kg P ha^{-1}, 71 kg K ha^{-1} and 5000 kg of Calcitic Lime ha^{-1}.

Irrigation was done by flooding water through field furrows in all treatments. Time was used to control the amount of water applied to each treatment in accordance with the requirements and specifications of that particular treatment. BVIS land has a slope of less than 1% making it gently sloping to almost flat. When irrigating, water was diverted from the field canal into the furrows through a field inlet and allowed to flow. The field inlet was closed once the flow had covered one third of the furrow down the slope.

2.4 Experimental Design

In this research, a randomized complete block design (RCBD) was used in the design of experiment. Plots were classified into three blocks or groups. Treatments were randomly assigned to each block such that each treatment occurred the same number of times but only once in each block. Four treatments were randomly assigned to each block and they were replicated three times. The tertiary and field canals are not lined, they are earth canals. In terms of proximity to the field plots, the tertiary canal was 100 cm and the field canal 40 cm away.

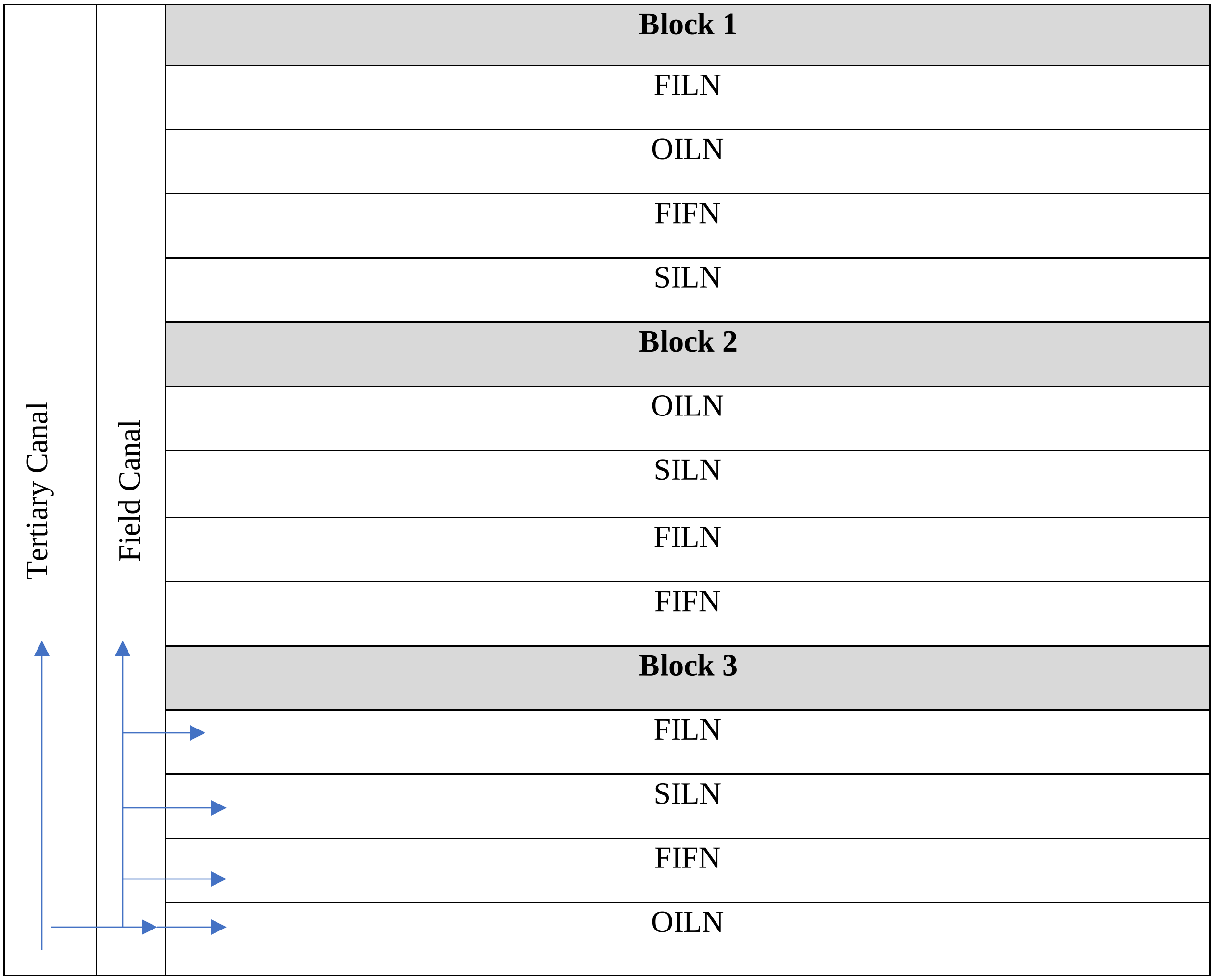


Figure 2. 2: Blocks and plots layout for maize trial in BVIS

2.5 Field Plot Preparation and Layout

Rice residues in the field were hand cleared using slashers. Soil was hand tilled using hoes and pick axes. Soil was tilled to a depth of approximately 20 to 30 cm. Twelve plots of 3 by 25 m in size were demarcated using a measuring tape and wooden pegs. These plots were then grouped into three blocks, thus four plots in each block as shown in figure 2.2 above.

Calcitic lime (5000 kg ha^{-1}) was applied to FILN, OILN and SILN in all three blocks after assignment of treatments. Ridges and furrows were constructed in all plots using hoes. Each ridge was 25 m in length and 20 cm in height. Furrows were 25 m in length and 30 cm in depth, from the top of the ridge. Both ridges and furrows were spaced 75 cm apart, and in each plot, there were four ridges and furrows. Twelve wooden field sign posts, each bearing the name of the treatment were installed in all plots.

2.6 Installation of Water Monitoring Tools

After field plot preparation, Wetting Front Detectors were installed in all twelve plots. Each plot had one pair of WFDs, one placed at a shallow depth of 20 cm, halfway in a ridge side and the other at a deeper depth of 40 cm. It must be noted that it is recommended that WFDs are always installed in pairs when used for irrigation scheduling. Soil augers and hoes were used to make holes into which the WFDs were installed. Figure 2.3 shows how the WFDs were installed in all plots.

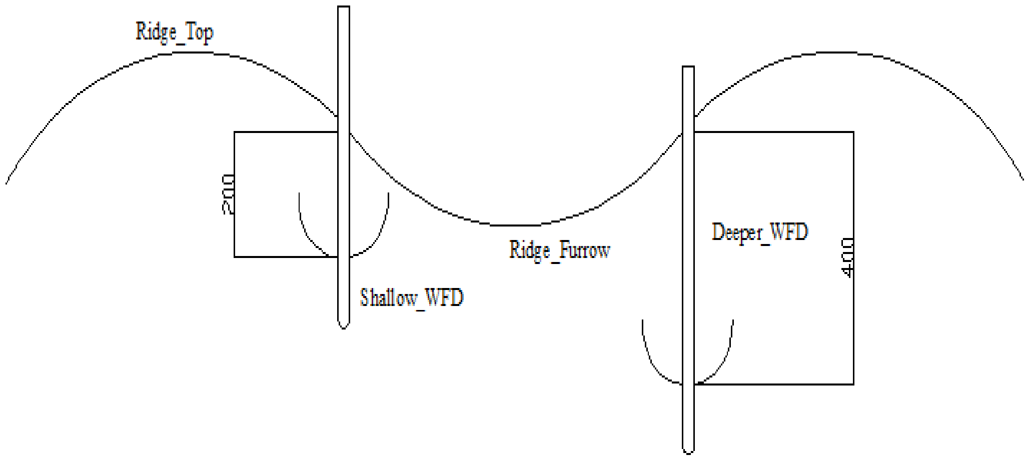


Figure 2. 3: Sketch showing field installation of WFDs (all dimensions are in mm)

Chameleon Sensors were installed close to WFDs in all plots. In each plot, a hole of up to 120 cm was drilled using a 50 mm diameter soil auger. In this hole, six Chameleon Sensors and two temperature sensors were placed at different depths. Sensors were placed at 20, 40, 60, 80, 100 and 120 cm. Two temperature sensors were placed at 40 and 80 cm along with Chameleon Sensors. All the sensors were placed in one hole but at different depths. The first sensor to be placed was the one at 120 cm, after which the soil was refilled and thoroughly compacted. In the same order, all the sensors were installed finishing with the one at 20 cm. Figure 2.4 shows a Chameleon reader and sensor array.

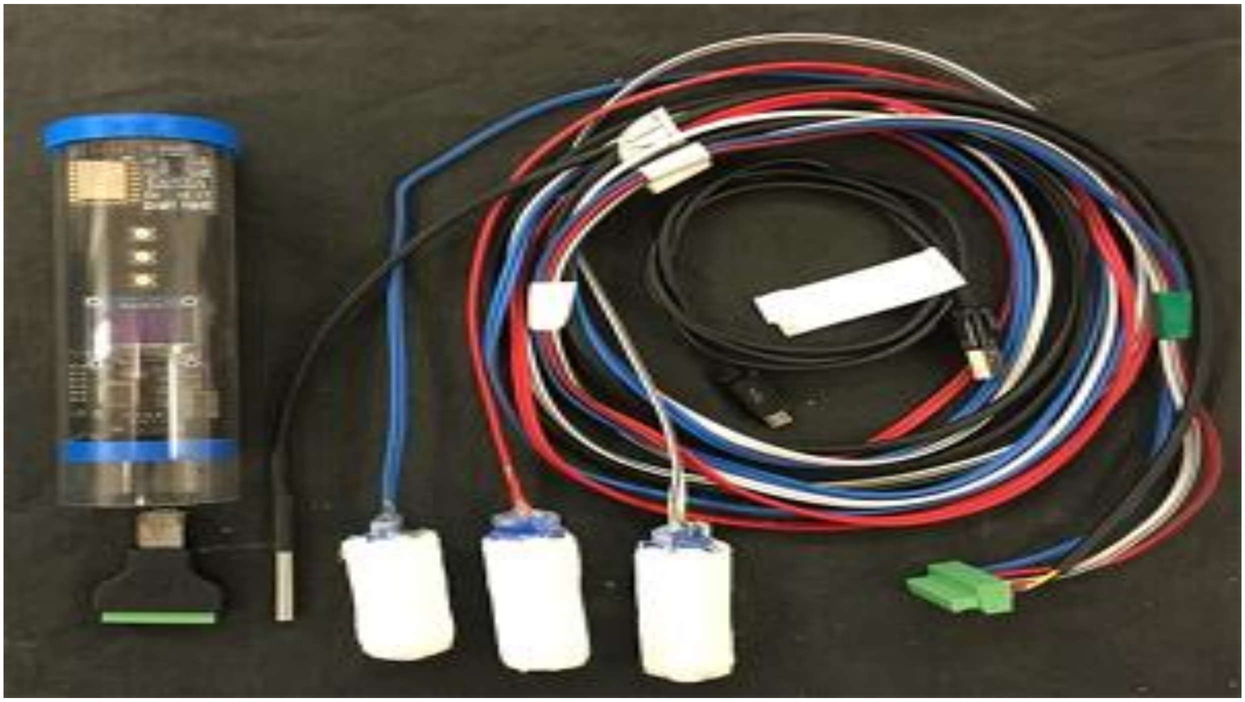


Figure 2. 4: Chameleon Reader and Sensor Array (Via.farm 2016a)

A portable Parshall Flume was temporarily installed at the field inlet of each plot whenever water was being applied to the plot. The Parshall flume was made out of wood and painted. After irrigation, the Parshall Flume was removed and stored at a safe location until the next irrigation. Water was applied to plots based on the demands and requirements of that particular treatment. Applied water was controlled using time. Figure 2.5 shows dimensions and sections of the Parshall Flume.

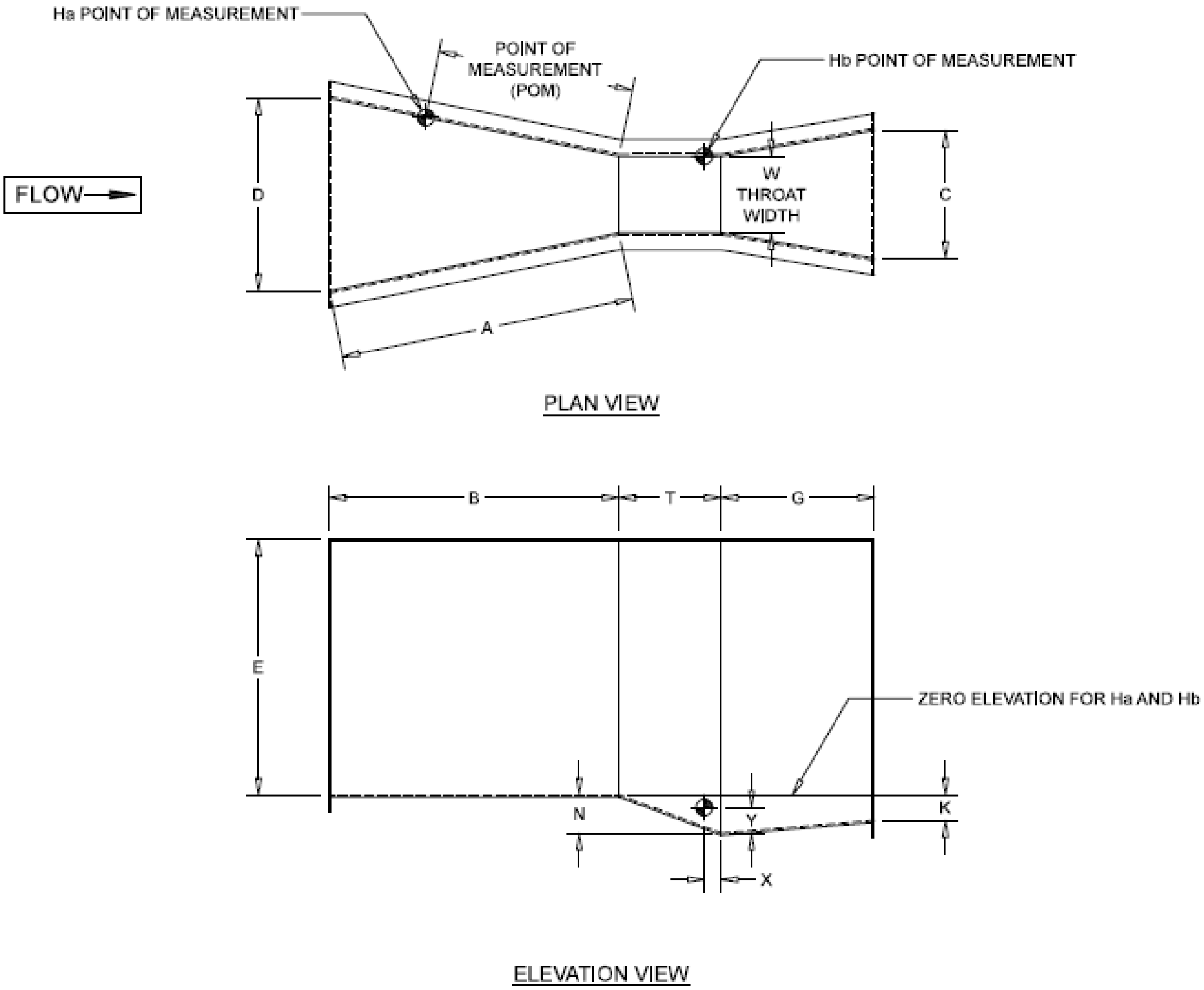


Figure 2. 5: Parshall Flume dimensions (Robinson 1957)

Fields were fully drained with soil evaporation drying the top soil when this trial commenced. Therefore, after all land preparation was completed and equipment installed, all plots were irrigated with 180 mm of water to ensure that the trial started with a wet soil profile. This was done to emulate wet soil conditions present soon after flooded rice harvest. Thereafter, the crop was planted.

Maize cultivar SC403 seeds were planted on top of ridges. One seed was planted in one planting station at approximately 5 cm deep. Planting stations were spaced at 25 cm apart along the ridge and 75 cm between the ridges. This plant spacing gave a seeding density of 53333 plants per ha. Planting was done on 4th August, 2017, three months after rice harvest.

Utilization of wet soil profile through early planting to grow maize was tested using a desktop analysis. Cropwat and Climwat models were used to test the effect of planting date on the total irrigated area in winter.

In the treatment receiving luxury nutrients, 180 (60 * 3) kg N ha^{-1}, 130 kg P ha^{-1} and 71 kg ha^{-1} was applied. Fertilizers were spread near planting stations and then incorporated into the soil with 15 to 18 mm of irrigation water. FIFN received 104 kg N ha^{-1}, 24 kg P ha^{-1}, 0 kg K ha^{-1} and 17 kg S ha^{-1}. The source of N, P, and K was inorganic fertilizers NPK (23:21:0+4S) and Urea (46%N). Calcitic lime was bought from Balaka Lime Factory in Balaka District, Malawi. The method of application was the same for all treatments. Figure 2.6 shows the planted maize trial.

Figure 2. 6: Maize trial

Hand weeding was done twice in all plots, 5 weeks and 9 weeks after planting. Cypermethrin was sprayed in all plots to control pests which were observed in adjacent farmer fields. This was the recommendation by the extension department and the spraying was done under supervision of a field extension officer.

2.7 Data Collection

2.7.1 Crop

Plant height was measured every two weeks after germination and recorded. Measurement was done manually using a measuring tape. Canopy cover was measured and recorded every two weeks after germination. It was measured using Canopeo. Canopeo is an application used to measure plant canopy cover. It is downloaded and installed on a smartphone. Canopy cover was measured by opening the application, using a phone camera, aerial photos or videos of the crop were taken. The application loaded and processed the photos or videos to give canopy cover as a percentage. The app can be downloaded from google play store online at www.canopeoapp.com. Figure 2.7 shows Canopeo application when opened on a smartphone.

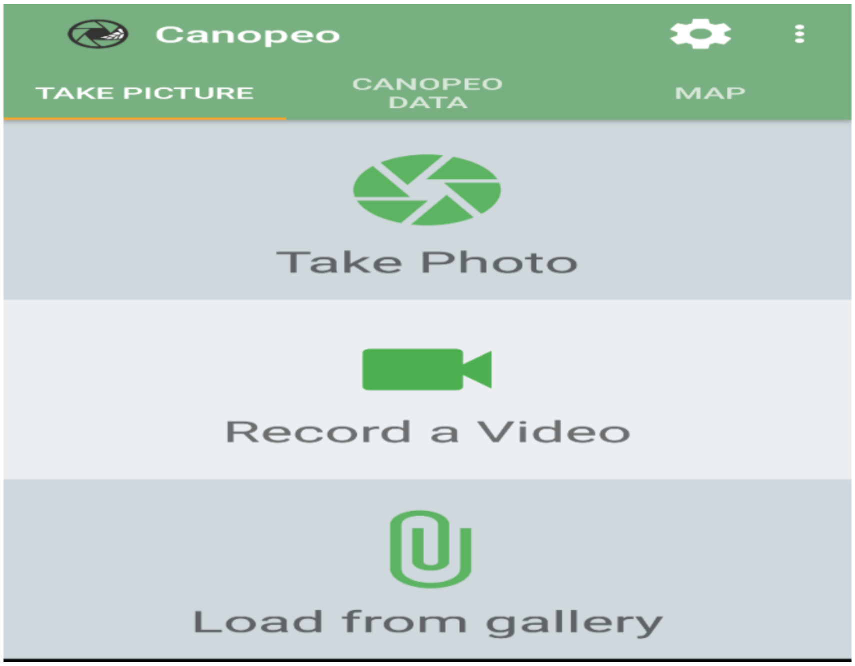


Figure 2. 7: Canopeo app opened on a smartphone screen (OSUAppCentre 2015)

At harvest, maize grain dry mass was measured and recorded. Plants were cut down in all plots and stacked. All plants from the borders were kept separate and not included in the measurement. Only plants from the middle of the plot were weighed. Maize grain was separated from the cobs and stalks, then weighed. This gave a field dry mass which was recorded. At field dry mass, the grain has 12-18% moisture content (du Plessis 2003) which was reduced by 21-day natural sun drying. All these measurements were done at the same time in all 12 plots.

2.7.2 Setting-up a farm on the Via.farm website

Firstly, one needs to register and obtain login credentials. Once logged in, the farm can be configured, an irrigation bay created, sensor arrays added and crop data entered. Sensor Arrays can be added manually or by “claiming” them using a Wi-Fi connection. Nitrate data is uploaded manually on the website, while water data is uploaded automatically after connecting the Chameleon reader to a Wi-Fi access point or a smartphone Wi-Fi hotspot.

2.7.3 Nutrients

After every irrigation event, if WFDs were activated, water was extracted from the WFD reservoir using a syringe. The extracted soil solution was then analyzed using nitrate test strips to check the levels of NO_3 in the soil. The results were recorded and uploaded on the VIA Farm website.

2.7.4 Water

Soil water tension was monitored once every three days in all plots using Chameleon colours. The Chameleon reader was plugged into sensor cables, and displayed different colours. The data was temporarily stored locally in the reader and later uploaded to the VIA farm website using a Wi-Fi connection.

A Parshall flume was used to record the amount of water received by a plot when it was irrigated. The flume was temporally installed at the inlet of the plot to be irrigated. Once water started flowing through it into the plot, several water level depths measurements at point H_a were recorded and averaged. This averaged value was then used in the equation, $Q = KH_a^n$, to calculate discharge in $m^3\ s^{-1}$. In the equation, Q is the free flow rate in $m^3\ s^{-1}$, K is the flume discharge constant (varies with flume size), H_a is the depth at point of measurement in metres, and n is the discharge exponent (depends on flume size). K and n values are obtained from empirical Table 1.3 (in Chapter 1, Literature Review) depending on the flume throat size. Time taken to irrigate the whole plot was also recorded. The recorded time in seconds, was then multiplied with the calculated discharge Q in $m^3\ s^{-1}$ to get the volume of water in m^3.

Rainfall, wind speed, humidity and sunshine data were obtained from Salima Meteorological Station which is 40 km away from the scheme.

Chapter 3: Nutrients and maize yield

3.1 Overview

In this chapter, the effect of nutrients on maize yield will be discussed. It has been reported that BVIS soils have sufficient levels of potassium (K), hence there is zero application of K by farmers in irrigated winter maize cropping (DAES 2015, DoI 2015). This is also the case for many small-scale irrigation schemes in Malawi. Nutrients applied by BVIS farmers and other small-scale irrigation scheme farmers in Malawi, are mainly based on guidelines provided by the Ministry of Agriculture, Irrigation and Water Development, through a document called the Guide to Agricultural Production (GAP). According to DAES (2015), du Plessis (2003) and SeedCo (2010), apart from nutrients, maize yield will also depend on other factors like planting method and plant density, weeding, herbicides, pesticides, water, temperature and soils. In this experiment, all other production factors except nutrients and water management were similar in all treatments.

BVIS maize yield observed on Via.Farm (2016b) was below average when compared to yields suggested by the SeedCo agronomy manual (producer of the maize cultivar SC403 used by BVIS farmers) and the FSSA handbook under the same growing conditions. Based on this information, it is believed that maize yield under current farmer practice in BVIS is suboptimal. In this experiment, this hypothesis was tested by varying nutrients and water applied to maize plots while other agronomic practices were kept the same. Some plots received the exact amount of nutrients as applied by the farmers (FN) and other plots received amounts as suggested by literature and also based on soil test results (LN). Maize yield results from all plots were analyzed using analysis of variance (ANOVA. Based on Anova results, the hypothesis will either be rejected or accepted. The discussion highlights the possible causes of low maize yield in BVIS and other small-scale irrigation schemes with similar conditions to BVIS. Suggestions on how to increase the yield of maize and lessons learnt are also discussed.

3.2 Field results

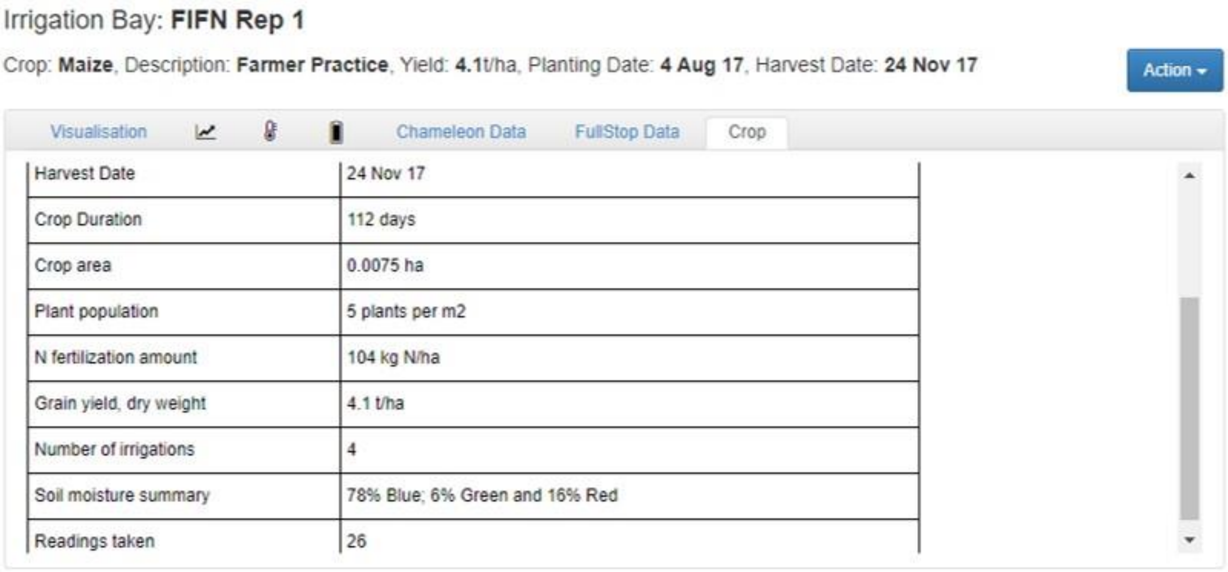
Tables 3.1 and 3.2 show soil test results carried out prior to the trial and maize yield obtained from all plots in three blocks respectively. Soil sampling was done in all three blocks and samples were analyzed at Chitedze Agricultural Research Station. Soil samples were taken from top and sub soil depths which were 0-20 cm and 20-60 cm respectively. Maize was harvested from all treatments on 24 November 2017. After harvest, the grain was sun dried for 21 days and weighed and recorded. Harvesting was done manually by field labourers and threshing was done by hand. A hanging weighing scale was used. Dry grain yield in t ha^{-1} from three blocks was averaged and summarized for every treatment as shown in the table 3.2, and figures (3.1 and 3.2) below.

Table 3. 1: Soil test results, July 2017

Bwanje Valley Irrigation Scheme Soil Analysis Results - Chitedze Agricultural Research Station, P.O. Box 158, Lilongwe										
BC1	**pH**	**%OC**	**%OM**	**%N**	**P(ug/g)**	**K(Cmol/Kg)**	**K(mg/Kg)**	**%Clay**	**%Silt**	**BD g/cm3**
Top	5.79	2.41	4.15	0.21	74.93	0.18	70.18	27.64	5.05	1.31
Sub	5.87	2.97	4.13	0.21	75.34	0.16	60.78	24.49	9	1.35
BC2	**pH**	**%OC**	**%OM**	**%N**	**P(ug/g)**	**K(Cmol/Kg)**	**K(mg/Kg)**	**%Clay**	**%Silt**	**BD g/cm3**
Top	5.62	1.31	2.26	0.11	26.58	0.17	65.46	21.44	10.5	1.4
Sub	5.71	1.21	2.08	0.10	66.74	0.18	69.21	20.89	7.55	1.46
BC3	**pH**	**%OC**	**%OM**	**%N**	**P(ug/g)**	**K(Cmol/Kg)**	**K(mg/Kg)**	**%Clay**	**%Silt**	**BD g/cm3**
Top	5.95	1.32	2.28	0.11	86.34	0.15	57.85	22.09	8	1.64
Sub	6.37	1.19	2.06	0.1	74.8	0.16	60.97	21.54	7	1.65

Table 3. 2: Maize yield in t ha^{-1}

	Block I	Block II	Block III
FIFN	4.1	3.15	3
FILN	5.3	4.7	4.15
OILN	5.95	6.5	4.8
SILN	4.5	4.15	4.45

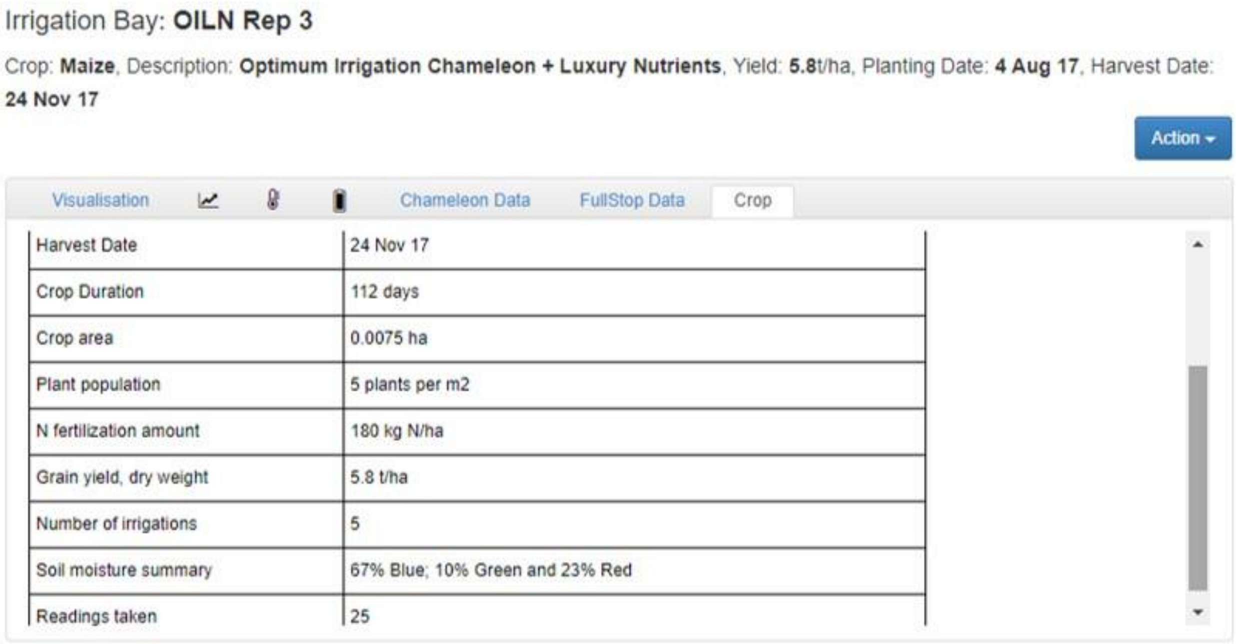


Irrigation Bay: **FIFN Rep 1**

Crop: **Maize**, Description: **Farmer Practice**, Yield: **4.1**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17**

Harvest Date	24 Nov 17
Crop Duration	112 days
Crop area	0.0075 ha
Plant population	5 plants per m2
N fertilization amount	104 kg N/ha
Grain yield, dry weight	4.1 t/ha
Number of irrigations	4
Soil moisture summary	78% Blue; 6% Green and 16% Red
Readings taken	26

Figure 3. 1: Maize data from FIFN (Via.farm 2017)



Irrigation Bay: **OILN Rep 3**

Crop: **Maize**, Description: **Optimum Irrigation Chameleon + Luxury Nutrients**, Yield: **5.8**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17**

Harvest Date	24 Nov 17
Crop Duration	112 days
Crop area	0.0075 ha
Plant population	5 plants per m2
N fertilization amount	180 kg N/ha
Grain yield, dry weight	5.8 t/ha
Number of irrigations	5
Soil moisture summary	67% Blue; 10% Green and 23% Red
Readings taken	25

Figure 3. 2: Maize data from OILN (Via.farm 2017)

Maize canopy cover and height was measured and recorded during the experiment. Appendices A and B show collected canopy and height data respectively and figures 3.3 and 3.4 show graphs of canopy cover and height against time in days respectively.

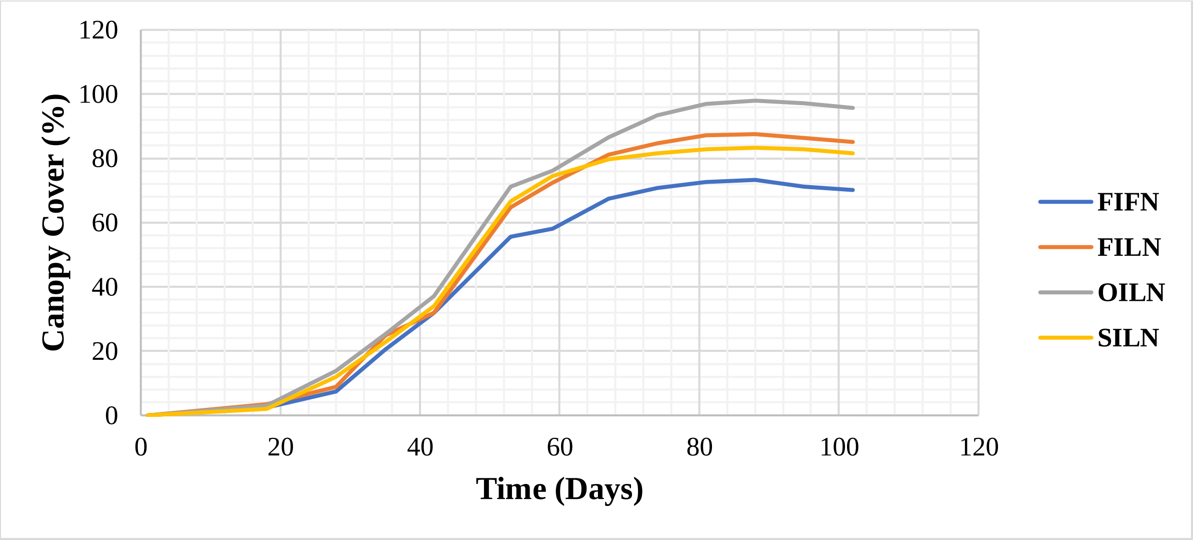


Figure 3. 3: Canopy cover against time in days

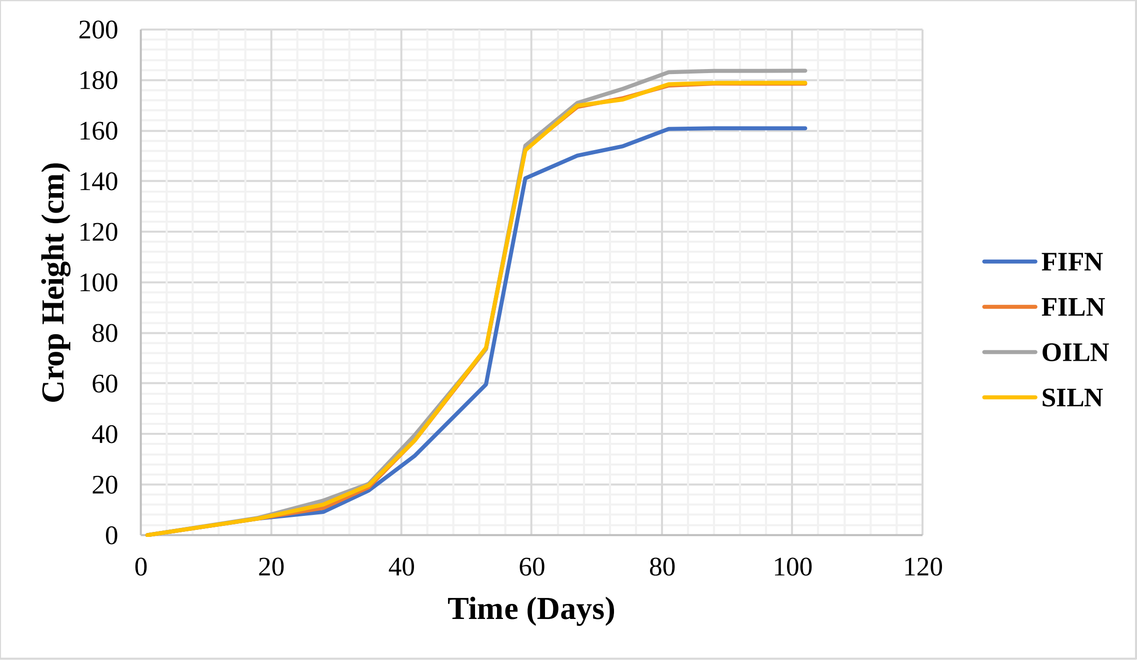


Figure 3. 4: Height against time in days

Figures 3.3 and 3.4 show that OILN produced the highest plant canopy cover and tallest plants while FIFN produced the least. There was very minimal difference between FILN and SILN.

3.3 Anova Output

Microsoft Office excel was used calculate analysis of variance. Table 3.3 below shows maize yields realized from all plots in three blocks.

Table 3. 3: Anova table of observations (maize yields in t ha^{-1})

Treatment	**Blocks**				
	I	**II**	**III**	**Total**	**Mean**
FIFN	4.1	3.15	3	10.25	3.42
FILN	5.3	4.7	4.15	14.15	4.72
OILN	5.95	6.5	4.8	17.25	5.75
SILN	4.5	4.15	4.45	13.1	4.37
Total	19.85	18.5	16.4	**55.75**	
Mean	4.96	4.63	4.1		**4.65**

Table 3. 4: Calculated ANOVA results on maize yields

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Blocks	0.75	2	0.38	2.34^{NS}	0.18	5.14
Treatments	10.98	3	3.66	22.79^{**}	0.001	4.76
Error	0.96	6	0.16			
Total	12.70	11				

Table 3.4 shows there was little or no variation in maize yields in t ha^{-1} among all three blocks i.e. F calculated (2.34) is less than F critical (5.14). There were highly significant differences in maize yield among the four treatments i.e. F calculated (22.79) is higher than F critical (4.76). Treatments which received luxury nutrients (FILN, OILN and SILN) produced higher yields than farmer nutrients (FIFN)

From table 3.2 and 3.3, the coefficient of variation (CV) was calculated using this formula; CV = √ (MSE) / ȳ * 100. In the formula, CV is coefficient of variation, MSE is error mean square and ȳ is grand mean. MSE from table 3.3 is 0.16 and grand mean from table 3.2 is 4.65. Therefore, CV = √ (0.16) / 4.65 * 100 = **8.63%**

Standard Error, SE which determines the level of precision at which the experiment was carried out, was calculated using MSE and r which is the number of blocks used in the experimental design. SE = √ (MSE) / r. From table 3.3, r is 3, hence SE = √ (0.16063) / 3 = **±0.13359.**

CV shows that the experiment is scientifically acceptable under field conditions, 8.63 % is less than 25 %. Low SE **±0.13359** indicates that the experiment was done with high precision in estimating the mean.

3.4 Treatment mean separation tests

Maize yield data from all treatments was subjected to SAS analysis which is a computer program to see which treatments differ significantly from each other. Tables 3.5 and 3.6 show the output from the program.

Table 3. 5: SAS, t test (least significant difference, LSD) for maize yield

Alpha	0.05
Error Degrees of Freedom	8
Error Mean Square	0.37
Critical Value of t	2.31
Least Significant Difference	1.14

Table 3. 6: SAS, treatment separation test (maize yield)

<table>
<tr><th colspan="5">Means with the same letter
are not significantly different.</th></tr>
<tr><th colspan="2">t Grouping</th><th>Maize Yield Mean</th><th>N</th><th>TRT</th></tr>
<tr><td></td><td>A</td><td>5.75</td><td>3</td><td>OILN</td></tr>
<tr><td></td><td>A</td><td></td><td></td><td></td></tr>
<tr><td>B</td><td>A</td><td>4.72</td><td>3</td><td>FILN</td></tr>
<tr><td>B</td><td></td><td></td><td></td><td></td></tr>
<tr><td>B</td><td>C</td><td>4.37</td><td>3</td><td>SILN</td></tr>
<tr><td></td><td>C</td><td></td><td></td><td></td></tr>
<tr><td></td><td>C</td><td>3.42</td><td>3</td><td>FIFN</td></tr>
</table>

Tables 3.5 and 3.6 show that OILN was significantly superior to SILN and FIFN, while SILN was not significantly different from FILN and FIFN at an alpha level of 0.05 and LSD of 1.14.

3.5 Discussion

From the Anova, it has been shown that blocking had no effect on maize yields. Under the same irrigated conditions, plots which received 180 kg N ha^{-1}, 130 kg P ha^{-1}, 71 kg K ha^{-1} and 5000 kg of Calcitic Lime ha^{-1} produced more maize per ha^{-1} than plots which received 104 kg N ha^{-1}, 24 kg P ha^{-1}, 0 kg K ha^{-1} and 17 kg S ha^{-1} which is the same amount of nutrients applied by BVIS farmers. Factors like weeding, planting method, pesticides and land preparation were the same in all plots. Soil test results indicated that BVIS soils are not very acidic, on average 5.6 pH, have low organic matter content (3.5 % on average), low nitrogen (0.1 – 0.2 %),) but sufficient phosphorus (26.5 -74.9 mg kg^{-1}). Soil potassium level (60.7 – 70.2 mg kg^{-1}) is lower than the recommended standard of 80 mg kg^{-1} to 120 mg kg^{-1}.

Maize yields were higher in this trial compared to farmers yields because of the luxury nutrients applied. Based on the yields obtained, it also shows that potassium may be the limiting factor in maize production for the scheme i.e. luxury nutrients which included potassium gave higher yields than farmer nutrients which had no potassium. WFDs helped to manage keep nitrates within the plant root zone.

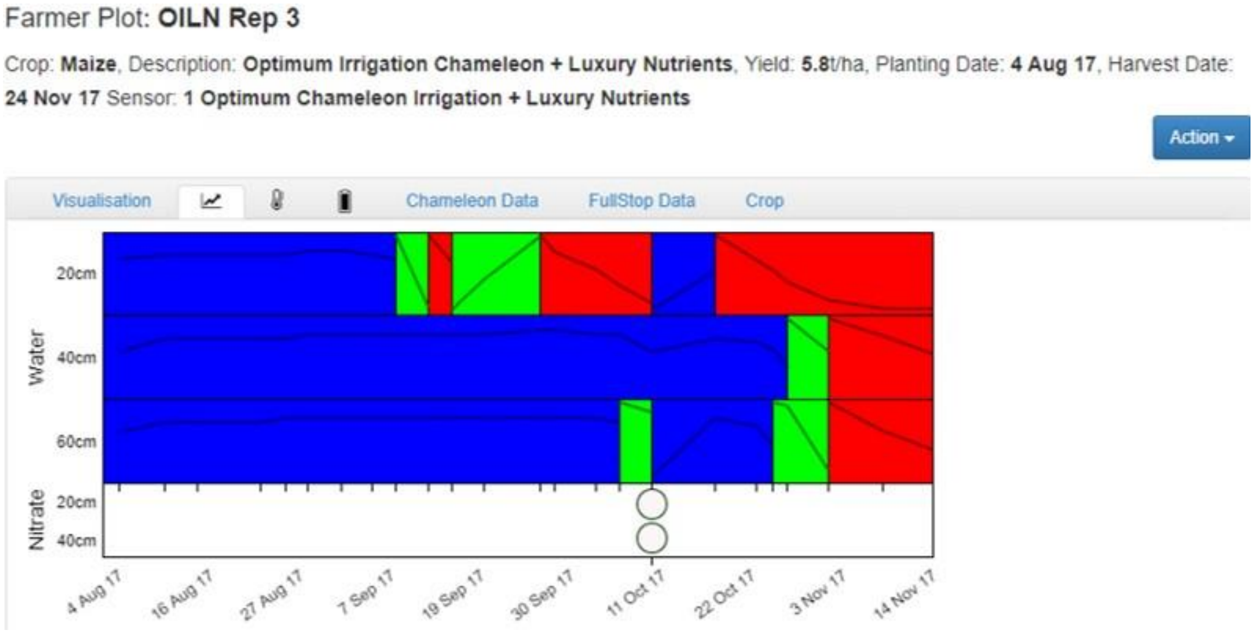
Table 3.7 shows a gross margin analysis on yields from farmer nutrients (FN) and luxury nutrients (LN). It must be noted that fertilizer prices are not subsidized and the maize price used in the calculations is what a farmer in Bwanje would pay currently. In the table, MK is Malawi Kwacha and $ or USD is United States of America Dollar. Other variable costs include labour charges, plot and water fees, cost of seed and pesticides.

Table 3. 7: Gross margin analysis for FN and LN (1 USD = 726 MK)

<table>
<tr><th colspan="9">Input Costs</th></tr>
<tr><th>Nutrient</th><th colspan="2">Input Description</th><th>Total inputs bag/ha</th><th>Input price MK/bag</th><th>Input cost MK/ha</th><th>Other variable costs MK/ha</th><th>Total Cost MK/ha</th><th>Total Cost USD/ha</th></tr>
<tr><td rowspan="3">FN</td><td colspan="2">NPK (23:21:0+4S)</td><td>6</td><td>25000</td><td>150000</td><td>50000</td><td>200000</td><td>275</td></tr>
<tr><td colspan="2">Urea (46%N)</td><td>8</td><td>25000</td><td>200000</td><td>50000</td><td>250000</td><td>344</td></tr>
<tr><td colspan="7">Total</td><td>620</td></tr>
<tr><td rowspan="4">LN</td><td colspan="2">NPK (23:21:0+4S)</td><td>4</td><td>25000</td><td>100000</td><td>50000</td><td>150000</td><td>207</td></tr>
<tr><td colspan="2">Urea (46%N)</td><td>4</td><td>25000</td><td>100000</td><td>50000</td><td>150000</td><td>207</td></tr>
<tr><td colspan="2">D-Compound (8:18:15)</td><td>9.5</td><td>26000</td><td>247000</td><td>50000</td><td>297000</td><td>409</td></tr>
<tr><td colspan="7">Total</td><td>822</td></tr>
<tr><th colspan="9">Revenue ha^{-1}</th></tr>
<tr><th>Treatment</th><th>Maize Yield kg/ha</th><th>Selling price MK/kg</th><th>Total Sales MK/ha</th><th>Total Sales $ ha^{-1}</th><th colspan="4">Profit (Total Sales – Total Cost) $ ha^{-1}</th></tr>
<tr><td>FIFN</td><td>3420</td><td>170</td><td>581400</td><td>801</td><td colspan="4">181</td></tr>
<tr><td>OILN</td><td>5750</td><td>170</td><td>977500</td><td>1346</td><td colspan="4">524</td></tr>
<tr><td>FILN</td><td>4720</td><td>170</td><td>802400</td><td>1105</td><td colspan="4">283</td></tr>
<tr><td>SILN</td><td>4370</td><td>170</td><td>742900</td><td>1023</td><td colspan="4">201</td></tr>
</table>

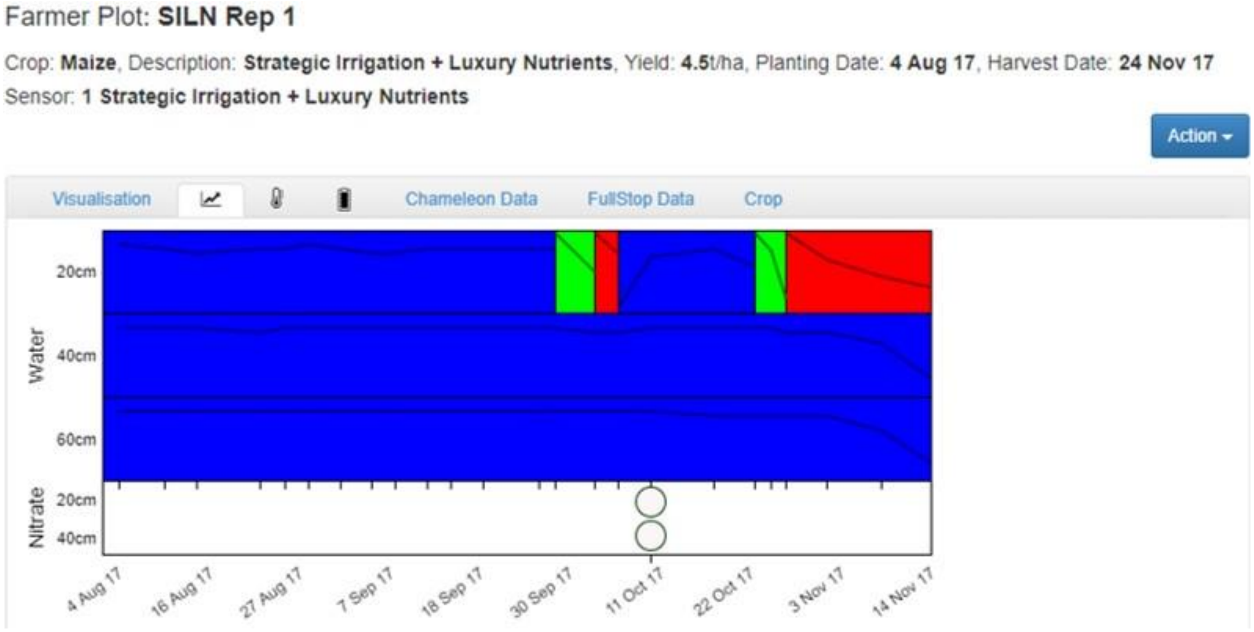
From this brief gross margin analysis, it is clear that economically, it would be more profitable to use LN rather than FN by BVIS farmers, but the optimum would likely be somewhere in between. Highest profits (\$524 ha^{-1}) are realized when LN are applied under optimum irrigation. Strategic irrigation (\$201 ha^{-1}) produced higher profits than farmer irrigation and nutrients (\$181 ha^{-1}) while applying LN under farmer irrigation produced slightly higher profits (\$283 ha^{-1}) than farmer irrigation and nutrients, but far less than optimum irrigation. This gross margin analysis has considered other minor costs including labour, plot and water fees, and pesticides.

No leaching was observed in the OILN and SILN treatments, as shown in Figures 3.5 and 3.6 below. Low level of nitrates was detected in both shallow and deep layers. This shows that there was little movement of nitrates into deeper soil layers and maximum uptake of nitrates by plant roots. For more details on leaching in OLIN and SILN, refer to Appendices I, J, K, L, M and N.


Farmer Plot: **OILN Rep 3**

Crop: **Maize**, Description: **Optimum Irrigation Chameleon + Luxury Nutrients**, Yield: **5.8**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17** Sensor: **1 Optimum Chameleon Irrigation + Luxury Nutrients**

Figure 3. 5: WFD nitrate data for OILN (Via.farm 2017)

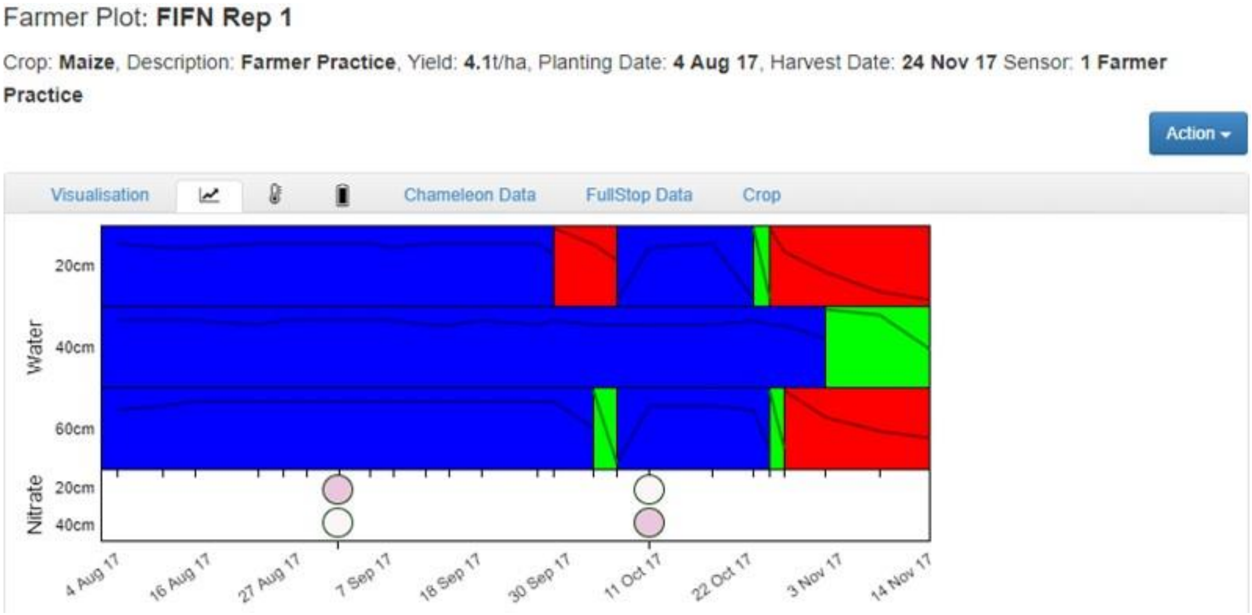

Farmer Plot: **SILN Rep 1**

Crop: **Maize**, Description: **Strategic Irrigation + Luxury Nutrients**, Yield: **4.5**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17** Sensor: **1 Strategic Irrigation + Luxury Nutrients**

Figure 3. 6: WFD nitrate data for SILN (Via.farm 2017)

On the other hand, leaching of nitrates was observed in FIFN and FILN and was due to over irrigation. Water sample extracted from WFD reservoirs indicated a high concentration of nitrates in the early stages of the experiment at 20 cm. Nitrates were then later detected at 40 cm. It must be noted that testing was done using nitrate strips a day after an irrigation event.

More detail is shown in figures 3.7 and 3.8. Refer to Appendices C, D, E, F, G and H for further details on FIFN and FILN nitrate data.



Farmer Plot: **FIFN Rep 1**

Crop: **Maize**, Description: **Farmer Practice**, Yield: **4.1**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17** Sensor: **1 Farmer Practice**

Figure 3. 7: WFD data for FIFN (Via.farm 2017)

Farmer Plot: **FILN Rep 1**

Crop: **Maize**, Description: **Farmer Irrigation + Luxury Nutrients**, Yield: **5.3**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17** Sensor: **1 Farmer Irrigation + luxury Nutrients**

Figure 3. 8: WFD data for FILN (Via.farm 2017)

Leached nutrients in FIFN reduced yields when compared to OILN. Chameleon Sensors also played a part in improving yields for OILN and SILN because optimum water required by crops was applied and monitored. Plants were irrigated only when there was a need to which reduced leaching and kept nutrients within the plant root zone. On average, FILN and FIFN received 488 mm, with OILN receiving 255 mm and SILN 235 mm of water during the season. Based on these results and analysis of variance, it is evident that maize yields under given farmer irrigation practice in BVIS are nutrient limited. Therefore, a null hypothesis that maize yield under current farmer practice in BVIS is not nutrient limited is rejected.

Over irrigation by farmers in BVIS which is due to a lack of soil water monitoring tools and because they are worried the river will stop running. This could also be the cause of acidic soils, among other factors. Over irrigation leaches nitrogen in nitrate form, into deeper layers of the soil. This leaves the soil very acidic. Acidic soils affect availability of nutrients which in turn impacts on crop growth. Maize prefers a pH range of 6 to 7.2 and a pH level of less than 5 will affect the crop. For BVIS, soil acidity could be reduced through prevention of over irrigation and application of agricultural lime.

The use of Chameleon Sensors and WFDs by BVIS farmers could help to reduce or prevent over irrigation. Farmers need to consider application of crushed limestone or any liming material to the soil, as it is a practical way to neutralize soil acidity. Depending on the availability of the lime material, farmers in BVIS should consider addition of lime to their plots in winter irrigation cropping though in general, pH is not the main issue but will become a problem soon or later because of the way they are managing their irrigation water. In this experiment, plots which were managed with WFDs, Chameleon Sensors and in which agricultural lime was added to soil produced high yields. These high yields are mainly because of addition of potassium to the soil (which evidently is the limiting factor based on the results of this experiment) and good irrigation water management using WFDs and CSs.

The nutrients currently applied by farmers in BVIS are not sufficient to realize the potential yields for maize. The guide to agricultural production recommends less or zero application of potassium to the soil for maize cropping. Higher maize yields were produced by adding more nutrients, including potassium. Nutrients (104 kg N ha^{-1}, 24 kg P ha^{-1}, 0 kg K ha^{-1} and 17 kg S ha^{-1}) applied by the farmers yielded on average 3.4 t ha^{-1} against 5.75 t ha^{-1} which was yielded by applying 180 kg N ha^{-1}, 130 kg P ha^{-1}, 71 kg ha^{-1} and 5000 kg Calcitic Lime ha^{-1}. This is consistent with the plant canopy cover and height observed during the trial. Luxury nutrients gave greater crop canopy cover and produced taller plants than did farmer nutrients.

The soil fertility data used in recommending amounts of nutrients to be applied to maize was established a long time ago and may not represent the current soil nutrient status. The Malawi Government through the Department of Agricultural Extension Services recommends site specific soil tests to be done before any crops are grown. This rarely happens because it is expensive. Normally, tests are supposed to be done by government technicians positioned centrally in government laboratories. Land owner/s have to pay all costs incurred by these technicians to carry out the activity on their piece of land. Prior to the trial, soil tests indicated low potassium levels and acidic soils, which is contrary to what is indicated in literature highlighted in Chapter 1. During the trial, it was observed that crop residues after harvesting were not returned to the soil, but instead are burnt. This is a general practice in irrigated and rain-fed farming which of course is not approved by the Ministry of Agriculture, Irrigation and Water Development. This practice mines nutrients from the soil, steadily reducing soil productivity. Worse still it contributes to greenhouse gas emissions (GHGs) and associate global warming. As a long-term solution, farmers need to start ploughing back crop residues after harvest to improve soil productivity and improve maize yields.

BVIS has an opportunity to increase maize yields by applying more nitrogen than what they currently apply because under this experiment more nitrogen application to the soil increased the yields. Potassium should be applied because it is evident that is not sufficient in BVIS soils. Yields would also be improved with the use of soil water and nutrient monitoring tools. BVIS should acquire Wetting Front Detectors and Chameleon Sensors which would help irrigation water and nutrient management which in turn would improve yields.

Chapter 4: Irrigation water and yields

4.1 Overview

Insufficient water supply to meet crop water requirements in BVIS in the dry winter season is one of the major problems faced by the scheme. The water source is the Namikokwe River, whose water flow drops significantly in the drier winter season (Jury et al. 2002, Veldwisch et al. 2009). Irrigation water management in BVIS is poor and a major challenge (Chidanti-Malunga 2009b). According to Chidanti-Malunga (2009a) poor water management in BVIS is caused by a lack of scheme ownership by farmers. Njoloma et al. (2009) indicated that water is poorly managed in BVIS because of poor operation and maintenance of the scheme's infrastructure.

In this chapter, seasonal irrigation water applied by farmers will be compared to seasonal irrigation water amount applied based on Chameleon Sensors. The aim is to establish whether BVIS farmers over irrigate their maize or not during the winter irrigation season. Based on analysis of the results, a hypothesis that under current farmer practice maize is over irrigated and nutrients are leached will either be rejected or accepted.

The amount of water applied to each treatment for the whole season will be calculated across all four treatments. A comparison will also be made in relation to yields realized by each of these treatments. Maize yield, total seasonal irrigation water applied and leaching for each treatment will be compared to ascertain whether farmers over irrigate or not.

A complete randomized block design was used to analyze the yields obtained from all treatments through analysis of variance (ANOVA). Based on the results, it can be determined whether blocking was necessary or not and if indeed there were significant difference in water use among the treatments.

4.2 Field Observations

4.2.1 Seasonal Crop Water Use (mm)

All plots were irrigated with the same amount of water (180 mm) prior to planting to make sure that the soil profile was completely wet. Thereafter, each plot was irrigated based on treatment requirements. Amount of water applied to each plot was recorded using a Parshall Flume. Using the Parshall Flume Formula $Q = KH_a^n$ and the time taken to complete irrigating each plot, the volume of water applied in m^3 was calculated. The calculated volume (m^3) of water applied was later converted into depth units by dividing by the irrigated area (m^2). The Parshall Flume throat width was 15.24 cm, with a flume discharge constant (K) and discharge exponent (n) of 0.264 and 1.58, respectively. K and n values were obtained from Table 1.3 in chapter 1.

Detailed calculation of the amount of water applied with each irrigation event in all plots using the above mentioned Parshall Flume method are given in Table 4.1 below. It must be noted in the table that FIFN and FILN had three irrigation events and small amounts of water were applied to incorporate fertilizer in the soil on 14/08/2017 and 19/09/2017. OILN and SILN had two irrigation events and small irrigations to incorporate fertilizers in the soil on 14/08/207 and 19/09/2017. More details are presented in Table 4.1 below.

Table 4. 1: Detailed calculation of water amounts applied to plots during the experiment

Irrigation Events: Water was measured using a Parshall Flume in all plots. Parshall Flume throat size was 15.24 cm, K (0.264) and n (1.58) values are from Table 1.3 in Chapter 1						
Treatment	**H_a (Averaged depth at point of measurement in m)**	**Time (s)**	**Date of Irrigation**	**Q $m^3 s^{-1}$ ($Q = KH_a^n$)**	**Water Applied (m^3) = Q ($m^3 s^{-1}$) * times (s)**	**Water Applied (mm)**
FILN R1	0.107	1747	02/08/2017	0.00773	13.50	180
	0.107	1440	28/08/2017	0.00773	11.13	148
	0.098	1338.6	10/10/2017	0.00673	9.00	120
	0.105	180	14/08/2017	0.00750	1.35	18
	0.097	180	19/09/2017	0.00662	1.19	16
OILN R1	0.107	1747	02/08/2017	0.00773	13.50	180

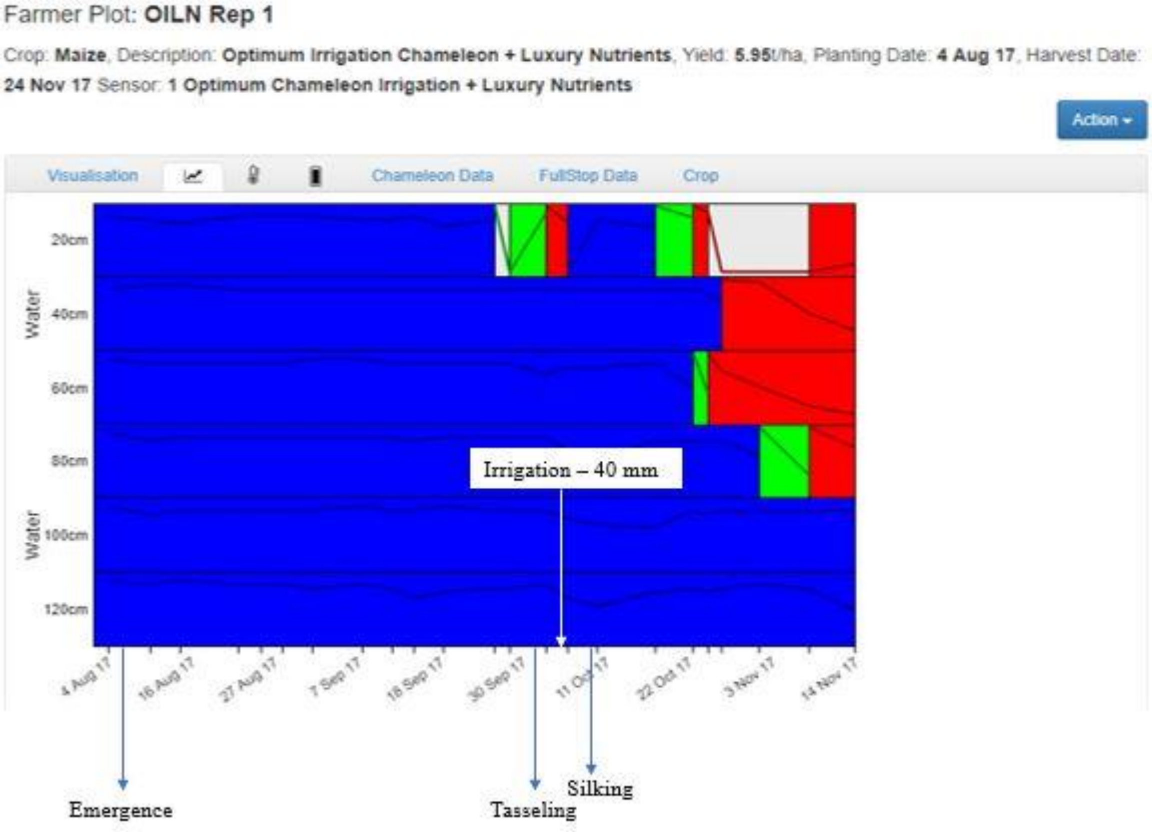
	0.099	439	10/10/2017	0.00683	3.00	40
	0.106	185	14/08/2017	0.00761	1.41	19
	0.098	182	19/09/2017	0.00673	1.22	16
FIFN R1	0.107	1747	02/08/2017	0.00773	13.50	180
	0.119	1320	28/08/2017	0.00914	12.07	161
	0.098	1338.5	10/10/2017	0.00673	9.00	120
	0.105	183	14/08/2017	0.00750	1.37	18
	0.098	181	19/09/2017	0.00673	1.22	16
SILN R1	0.107	1747	02/08/2017	0.00773	13.50	180
	0.099	220	10/10/2017	0.00683	1.50	20
	0.106	180	14/08/2017	0.00761	1.37	18
	0.097	184	19/09/2017	0.00662	1.22	16
OILN R2	0.107	1747	02/08/2017	0.00773	13.50	180
	0.099	439	10/10/2017	0.00683	3.00	40
	0.105	183	14/08/2017	0.00750	1.37	18
	0.098	186	19/09/2017	0.00673	1.25	17
SILN R2	0.107	1747	02/08/2017	0.00773	13.50	180
	0.099	220	10/10/2017	0.00683	1.50	20
	0.105	182	14/08/2017	0.00750	1.37	18
	0.098	188	19/09/2017	0.00673	1.26	17
FILN R2	0.107	1747	02/08/2017	0.00773	13.50	180
	0.118	1370	28/08/2017	0.00902	12.36	165
	0.098	1338.5	10/10/2017	0.00673	9.00	120
	0.106	187	14/08/2017	0.00761	1.42	19
	0.097	186	19/09/2017	0.00662	1.23	16
FIFN R2	0.107	1747	02/08/2017	0.00773	13.50	180
	0.114	1350	28/08/2017	0.00854	11.53	154
	0.097	1360.5	10/10/2017	0.00662	9.00	120
	0.105	187	14/08/2017	0.00750	1.40	19
	0.098	186	19/09/2017	0.00673	1.25	17
FILN R3	0.107	1747	02/08/2017	0.00773	13.50	180
	0.111	1345	28/08/2017	0.00819	11.01	147
	0.097	1360.1	10/10/2017	0.00662	9.00	120
	0.106	185	14/08/2017	0.00761	1.41	19

	0.098	186	19/09/2017	0.00673	1.25	17
SILN R3	0.107	1747	02/08/2017	0.00773	13.50	180
	0.098	223.1	10/10/2017	0.00673	1.50	20
	0.105	188	14/08/2017	0.00750	1.41	19
	0.098	187	19/09/2017	0.00673	1.26	17
FIFN R3	0.107	1747	02/08/2017	0.00773	13.50	180
	0.109	1366	28/08/2017	0.00796	10.87	145
	0.098	1338.5	10/10/2017	0.00673	9.00	120
	0.106	189	14/08/2017	0.00761	1.44	19
	0.099	186	19/09/2017	0.00683	1.27	17
OILN R3	0.107	1747	02/08/2017	0.00773	13.50	180
	0.099	439	10/10/2017	0.00683	3.00	40
	0.105	187	14/08/2017	0.00750	1.40	19
	0.098	186	19/09/2017	0.00673	1.25	17

It must be noted that the idea was to apply the same amount of water for each replicate of a treatment. This was difficult to achieve and control during the trial because of the method of irrigation (furrow flooding) used. This caused minor variations in amount of water applied to the same treatment across the three blocks. In Table 4.1 above, FIFN and FILN were irrigated the same way the farmers do. Farmers agreed to irrigate these plots, while amount of water going into these plots was recorded. It was observed that farmers irrigate 140 to 160 mm after every 21 to 28 days which translates to 5 and 7.6 mm day^{-1}. Under FIFN and FILN, irrigation was completely based on farmers experience and knowledge, and not based on WFDs and Chameleon Sensors installed. WFDs and Chameleon Sensors were installed in FIFN and FILN just to monitor nutrient leaching and soil water status, and not to help decide when and how much water to irrigate. Plots were also irrigated with small amounts of water to incorporate fertilizers into the soil (17 to 19 mm). For the whole irrigation season, on average, both FIFN and FILN received 488 mm.

OILN and SILN were irrigated purely based on Chameleon colours. These treatments were irrigated only once in addition to the wetting up of the soil profile and the small irrigation events (15 to 18mm) which were applied to incorporate fertilizers into the soil. For the first six or seven weeks, the Chameleon Sensors indicated sufficient water present in soil, with all soil layers displaying blue. Hence, no irrigation was applied during this period. On average, OILN received 255 mm, and SILN, 235 mm.

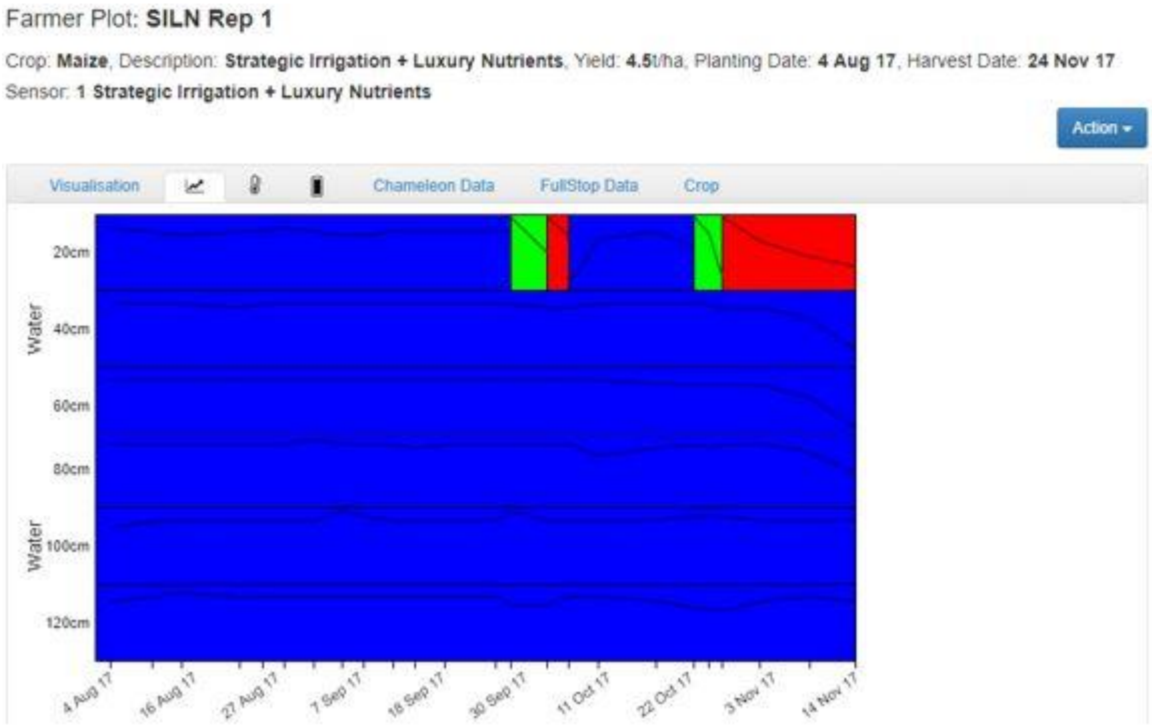
Du Plessis (2003) suggests that maize needs a minimum of 350 mm of water to mature. Maize in OILN and SILN, therefore, likely utilized residual soil water from deeper soil layers which was not recorded, in addition to the 255 and 235 mm applied, which explains why crops still matured with minimal irrigation, and the dominant Chameleon colour at depth (80 to 120 cm) was blue, almost throughout the experiment, as shown in Figures 4.1 and 4.2. These figures also show one irrigation event after planting, and at a few selected growth stages. In the top three soil layers (20, 40 and 60 cm), green and red Chameleon colours indicated drier soils. The soil became drier because of the increased water use as crops grew and increased surface evaporation rates caused by increasing temperatures. Refer to Appendices J, K, L, M, N and O for more information. Discussion in this section will be based on observed and recorded figures only.



Farmer Plot: **OILN Rep 1**

Crop: **Maize**, Description: **Optimum Irrigation Chameleon + Luxury Nutrients**, Yield: **5.95**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17** Sensor: **1 Optimum Chameleon Irrigation + Luxury Nutrients**

Figure 4. 1: Chameleon Sensor data visualization, OILN (Via.farm 2017)



Farmer Plot: **SILN Rep 1**

Crop: **Maize**, Description: **Strategic Irrigation + Luxury Nutrients**, Yield: **4.5**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17**
Sensor: **1 Strategic Irrigation + Luxury Nutrients**

Figure 4. 2: Chameleon Sensor data visualization, SILN (Via.farm 2017)

Figure 4.3 below shows the averaged total seasonal irrigation water applied to four treatments during the trial period. FIFN and FILN averaged the highest while OILN and SILN received much less irrigation water.

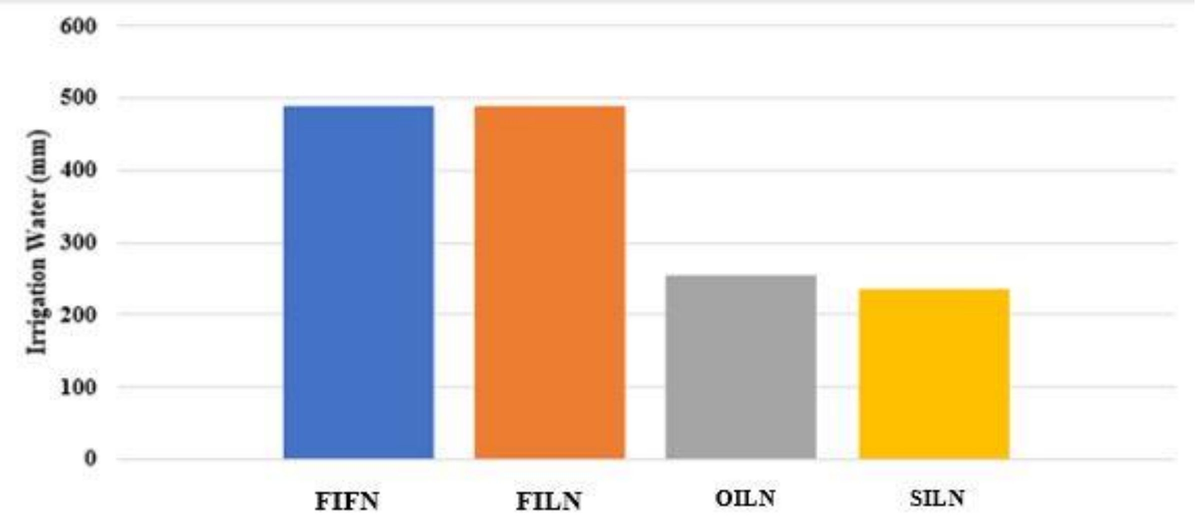


Figure 4. 3: Average seasonal irrigation water applied in mm

Figure 4.3 shows that farmer irrigation treatments received more water than irrigation based on the tools. In BVIS, farmers use local knowledge and experience without the assistance of any soil water monitoring tools to determine how much water to irrigate and when. When irrigating, farmers just irrigate their plots until they are satisfied that they have applied enough. This way of irrigating presents a greater chance of giving too much or too little water, than what the crop needs. Irrigating without tools can also result in farmers applying different amounts to the same crop under similar plot sizes and conditions. This results in leaching of nutrients which in turn reduces yield.

It can be seen from the results in Figure 4.3, that irrigation based on Chameleon Sensors reduces the seasonal irrigation crop water requirement by more than half. As indicated earlier, a minimum of 25 mm of water was applied to OILN while a minimum of 20 mm of water was applied to SILN with a little addition later on basing on the Chameleon Reader colours.

4.3 Analysis of Variance

Since maize yields to be used in this chapter are the same as those in chapter 3, results from Anova in chapter 3 will be used for discussion here in chapter 4 to avoid repetition. Irrigated water will be discussed in comparison to the same maize yields as presented in chapter 3.

From ANOVA in chapter 3, coefficient of variation (CV) is 8.63**%**, and standard error (SE) is **±0.13359** for yields. The CV indicates that the experiment is scientifically acceptable under field conditions, while low SE indicates that the experiment was done with good precision.

4.4 Treatments separation test

Water applied to all treatments was subjected to statistical analysis using the Statistical Analysis System (SAS) (Ref?) to determine which treatments differ significantly from each other. Tables 4.2 and 4.3 show the SAS computer output.

Table 4. 2: SAS, t test, LSD for irrigation water applied

Alpha	0.05
Error Degrees of Freedom	8
Error Mean Square	106.3
Critical Value of t	2.3
Least Significant Difference	19.4

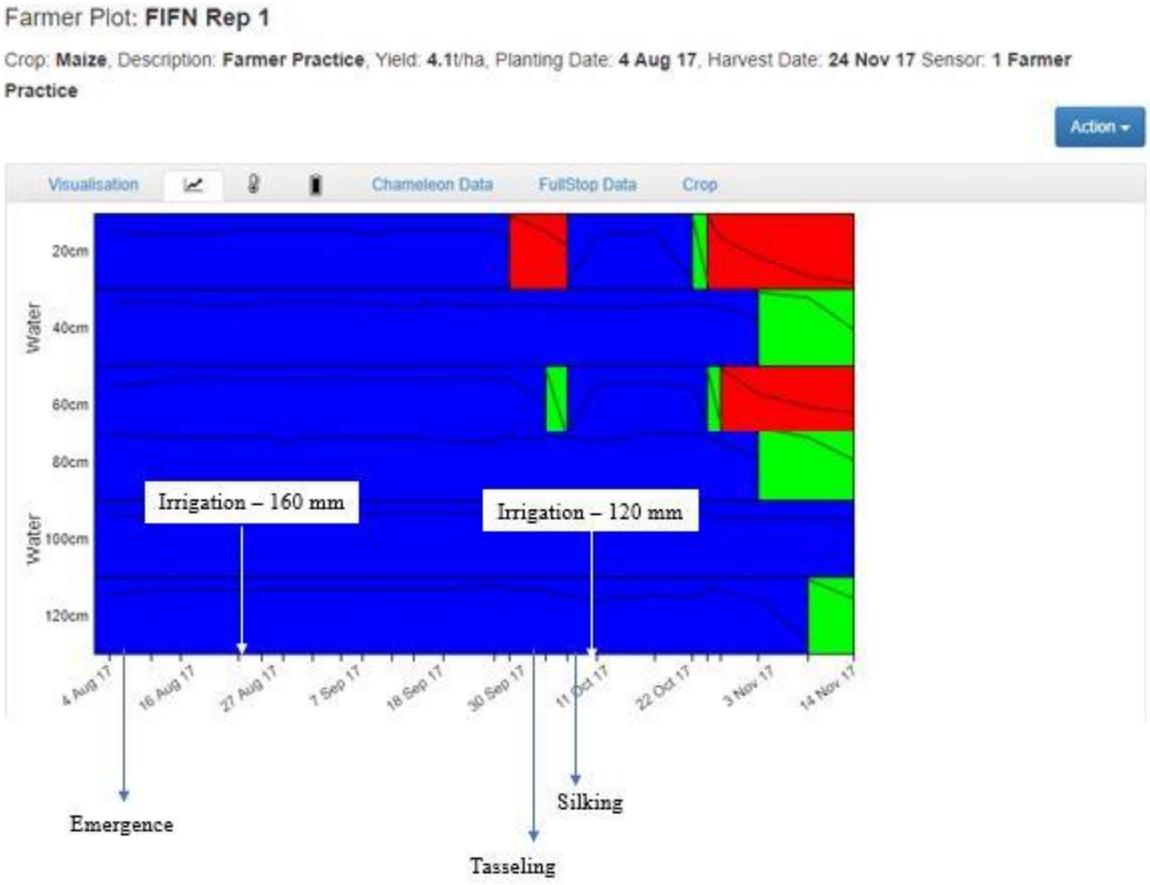
Table 4. 3: SAS, treatment separation test (irrigation water)

Means with the same letter are not significantly different.			
Duncan Grouping	**Mean**	**N**	**Water**
A	488	3	FIFN
A			
A	488	3	FILN
B	248	3	OILN
B			
B	241	3	SILN

At 0.05 Alpha level and 19.4 LSD, Tables 4.2 and 4.3 show that water applied to FIFN is not significantly different from that applied to FILN, but these are significantly different from that applied to OILN and SILN. It is also shown that water applied to OILN is not significantly different from that applied to SILN.

4.5 Discussion

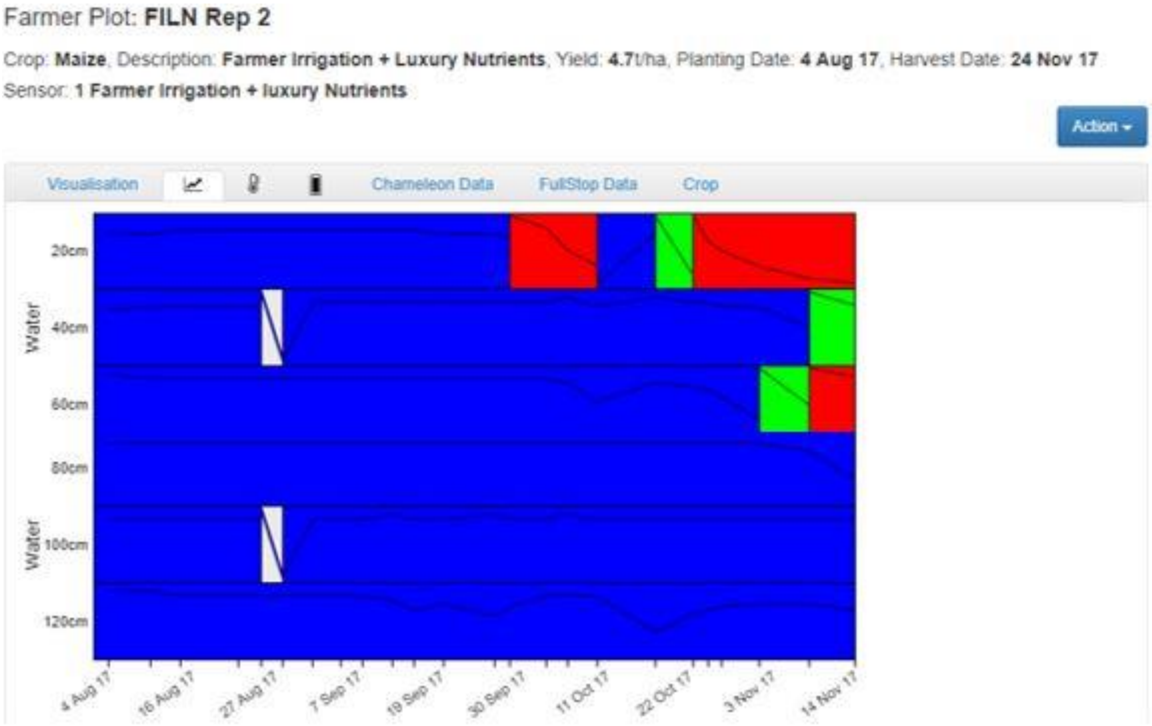
The analysis of variance shows there is no significant difference among the three blocks in irrigation water used. This means that blocking was not necessary in this experiment. Soil type, topography and other factors were uniform in all three blocks. From the analysis, it is also shown that there were highly significant differences in water among the four treatments. On average, OILN used 255 mm, while FILN and FIFN used 488 mm and SILN used 235 mm. It should be noted that higher yields produced by OILN were due to the combined effect of luxury nutrients managed by WFDs and optimum water application which was based on Chameleon Sensor colours. Figure 3.1 in Chapter 3 indicates over irrigation because the soil water summary of the Chameleon was 94% blue with yield of 3.1 t ha^{-1} while Figure 3.2 in the same chapter indicates a soil water summary of 67% blue with yield of 5.8 t ha^{-1}. Over irrigation was caused by lack of soil water monitoring tools, which leached nutrients and reduced yields. The hypothesis that maize is over irrigated under current farmer practice is accepted and the null hypothesis that maize is not over irrigated under current farmer practice is rejected. Figures 4.4 and 4.5 show more detail on yields, growth stages and water from four treatments. Refer to Appendices D, E, F, G, H and I for more information.



Farmer Plot: **FIFN Rep 1**

Crop: **Maize**, Description: **Farmer Practice**, Yield: **4.1**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17** Sensor: **1 Farmer Practice**

Figure 4. 4: Chameleon data on water and yields in FIFN (Via.farm 2017)



Farmer Plot: **FILN Rep 2**

Crop: **Maize**, Description: **Farmer Irrigation + Luxury Nutrients**, Yield: **4.7**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17**

Sensor: **1 Farmer Irrigation + luxury Nutrients**

Figure 4. 5: Chameleon data on water and yields in FILN (Via.farm 2017)

Results and analysis from the experiment show that farmers in BVIS apply more water in winter than is needed for maize production. This causes leaching of nitrates as observed during the experiment, which in turn reduces maize yield in BVIS.

Over irrigation in BVIS is mostly caused by a lack of soil water monitoring tools and methods which could guide farmers on how much water to apply and when to apply. As indicated in the background information, farmers in BVIS rely on their local irrigation knowledge and experience in scheduling their irrigation. They also use the feel-and-appearance method to determine level of water in the soil and decide whether they have to irrigate or not. Clearly, complete reliance on local irrigation knowledge, experience and the feel-and-appearance method is insufficient to prevent over irrigation and leaching of nitrates in BVIS.

Over irrigation in BVIS is also caused by the way the Water User Group (WUG) manages irrigation water in the absence of soil water monitoring tools. WUG is a farmer management committee which is formed by farmers themselves and is functional. The committee is responsible for water allocation, scheme maintenance and plot allocation. This committee is helped by a government agricultural extension worker stationed at the scheme and Irrigation

Officers from Dedza District Irrigation Office. What was noted during the trial is that this committee has an irrigation schedule calendar. It was developed by the committee itself with help from government officers in consultation with scheme members. This irrigation calendar is not observed or followed. Water is allocated to a member based on other preferences, rather than what the schedule says, and the status of available water in the soil profile. When irrigating, it was also noted that farmers in BVIS flood their furrows until all furrows in a 30 by 30 m plot are submerged and then wait for 21 to 28 days to irrigate again. There is no control on how much water each farmer should apply and when, which likely results in over irrigation and nutrient leaching.

Another cause for over irrigation observed during the trial period is limited support of irrigation extension service. BVIS is in Mtakataka Extension Planning Area, which is one of many Extension Planning Areas overseen by Dedza District Irrigation Officers. BVIS farmers have a low level of education, which makes frequent and close supervision by district irrigation officers crucial. Limited financial resources and time spent at the District Irrigation Office could also be the cause of this limited technical support to BVIS which is about 70 km from Dedza town, where the District Irrigation Office is located. Reinforcement of the irrigation calendar and direct constant supervision of irrigation by District Irrigation Officers would improve BVIS irrigation water management and reduce over irrigation. This would reduce leaching of nutrients and improve maize yield.

Higher maize yields were produced by scheduling irrigation using Chameleon Sensors. However, with the same amount of water and nutrients applied, SILN yielded much lower than OILN. At this stage, the cause of this depressed yield is not clear, and cannot be ascertained using the available data. Maize under these two treatments grew under very similar agronomic conditions (as shown by ANOVA analysis) and even chameleon colour patterns show minimal variations. The only suspected cause of this difference in yield from OILN and SILN is water interference from bordering farmer plots and the earth tertiary canal which ran across experimental plots, which unfortunately cannot be established retrospectively. Very minimal leaching of nitrate was observed throughout the experiment in plots managed by soil water monitoring tools. In the absence of monitoring tools, split application under irrigated and rainfed conditions can result in significant deduction of nitrate leaching. This was because over irrigation was reduced and water was only provided when the plants needed it. Reduced nutrient leaching, among other factors, was the most direct cause of higher maize yields from OILN. The predominantly blue colour from Chameleon Sensor readings in deeper soil layers (80, 100 and 120 cm) throughout the trial period indicates that the BVIS soil retains a lot of water after rice harvest. This may also be caused by the receding groundwater table, feeding water up into the soil profile through capillary rise. The initial 180 mm application could also have contributed to this wet condition. Looking at the difference in maize yields between plots managed using WFDs and Chameleon Sensors and those without, it can be said that simple soil water monitoring tools like Chameleon Sensors and WFDs can improve maize productivity in BVIS. In other words, farmer irrigation yielded less maize than irrigation based on simple soil water monitoring tools because nutrients were leached which was caused by over irrigation.

Use of Chameleon Sensors by farmers in BVIS would reduce over irrigation, reduce nitrate leaching and save irrigation water.

Chapter 5: Residual soil water utilization and irrigated area

5.1 Overview

The shortage of water and the resultant small area under irrigation in the winter season are of the problems highlighted earlier for BVIS (Chidanti-Malunga 2009b, Veldwisch et al. 2009). Only 145 ha out of 800 ha is irrigated in the winter cropping season as water from Namikokwe River runs out in October and November which, heavily impacts on the yield of maize and restricts the cultivated area. In this experiment, the possibility of expanding the area under irrigation in winter through careful residual soil water utilization was demonstrated with a Climwat and Cropwat desktop analysis. Maize yields on Via.farm (2016b) for BVIS indicated little difference between those planted in May or July. The timing of the academic programme made it difficult to have two planting dates as a treatment, hence, through a desktop analysis, expansion of irrigated area through residual soil water utilization was explored and demonstrated.

In the wet season, BVIS grows paddy rice in basins which is flood irrigated. Harvesting of rice is done from early April to the end of June, depending on planting date. It appears that based on literature and Chameleon data on Via.Farm (2016a), the soil profile is wet soon after rice harvest because of residual soil water present from summer rice cropping. This could be used to grow a crop with little or no irrigation if farmers consider planting soon after rice harvest. For some reason (not established from the farmers), BVIS farmers do not plant their maize soon after rice harvest, but instead wait for plots to dry (Chidanti-Malunga 2009a, Johnstone 2011). So, the question is, can residual soil water after rice harvest be utilized to grow maize in winter and reduce the irrigation requirement which would in turn save water and expand the cultivated area? Climwat and Cropwat were used to estimate the seasonal irrigation requirements from two planting dates using data from the nearest meteorological station.

Based on the output of this analysis and recorded seasonal irrigation water applied to plots, the hypotheses that irrigation area can be expanded by utilizing residual soil water and soil water monitoring tools will either be rejected or accepted.

5.2 Seasonal crop water used

Table 5. 1: Average irrigation water amount applied to each treatment in all three blocks

Treatment Description	Water (mm)
FIFN	488
FILN	488
OILN	255
SILN	235

Table 5.1 shows seasonal irrigation water used by all treatments. From the table, FIFN and FILN used more water than OILN and SILN

Anova

Table 5. 2: Observations on irrigated water

Table of Observations (Irrigation water in mm)				
	Blocks			
Treatment	**I**	**II**	**III**	**Mean**
FIFN	495.4	489.2	481.1	488
FILN	482.3	500.2	482.3	488
OILN	255.1	255	255.4	255
SILN	234.6	235.1	235.6	235
Total	1467.4	1479.5	1454.4	
Mean	366.8	369.8	363.6	**367**

Table 5. 3: Calculated Anova results using Microsoft excel

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Blocks	78.79	2	39.39	**0.99**^{NS}	0.42	**5.14**
Treatments	178164	3	59388.2	**1495.58****	5.2E-09	**4.76**
Error	238.26	6	39.71			
Total	178482	11				

Analysis results in Table 5.3 show that there were no significant differences in amount of water applied to treatments among all blocks i.e. F calculated (0.99) is less than F critical (5.14). The results also show that there were highly significant differences in amount of water applied among all treatments i.e. F calculated (1495.58) is greater than F critical (4.76). SAS analysis was done on water data to see which treatments differ significantly, in chapter 4 (Tables 4.2 and 4.3), and the output results show that OILN is not significantly different from SILN in terms of irrigation water received at an Alpha level of 0.05 and 19.4 LSD.

From Table 5.3 and Table 5.2 above, coefficient of variation (CV) was calculated by using the formula; CV = √ (MSE) / ȳ * 100. In the formula, CV is coefficient of variation, MSE is error mean square and ȳ is grand mean. MSE from table 5.3 is 55.4143 and grand mean from table 5.2 is 159.4567. Therefore, CV = √ (55.4143) / 159.4567 * 100 = **4.67%**

Standard Error, SE, which determines the level of precision at which the experiment was carried out, can be calculated using MSE and r which is the number of blocks used in the experimental design. SE = √ (MSE) / r. From table 5.2, r is 3, hence SE = √ (55.4143) / 3 = **±2.48**

5.3 Climwat and Cropwat output

Using Climwat data for Salima meteorological station, which is the nearest in terms of similarities in climate and elevation above sea level with BVIS, data in table 5.4 was calculated, showing monthly reference evapotranspiration ETo from January to December.

Table 5. 4: Cropwat estimation of monthly ETo for BVIS.

Month	Min Temp °C	Max Temp °C	Humidity %	Wind km/day	Sunshine hours	Radiation MJ/m²/day	ETo mm/day
January	21.4	29.4	80	147	5.9	19.5	4.2
February	21.3	29	82	147	6.2	19.8	4.1
March	21.4	29.5	77	181	7.4	20.8	4.4
April	20.7	28.9	73	216	8.7	20.8	4.4
May	17.9	27.8	68	207	9.5	19.7	4.1
June	15.9	26.2	63	225	9.3	18.2	3.8
July	15.8	25.9	61	225	8.9	18.2	3.8
August	16.9	27.8	57	216	9.7	21.2	4.6
September	18.7	30.6	55	207	10	23.9	5.4
October	21.3	32.5	54	225	10	25.4	6.2
November	22.3	32.2	61	216	9	24.3	6
December	22.2	30.3	75	173	6.7	20.7	4.7
Average	**19.6**	**29.2**	**67**	**199**	**8.4**	**21**	**4.64**

Table 5. 5: Crop evapotranspiration (ETc) for maize in BVIS from May to August from Cropwat

Month	Decade (10 days)	Stage	Kc coeff	ETc mm/day	ETc mm/dec	Eff rain mm/dec	Irr. Req. mm/dec
May	1	Init	0.3	1.26	8.8	6.5	4.2
May	2	Init	0.3	1.22	12.2	0.7	11.5
May	3	Dev	0.45	1.77	19.5	0.7	18.8
Jun	1	Dev	0.9	3.51	35.1	1.4	33.7
Jun	2	Mid	1.19	4.51	45.1	0.4	44.7
Jun	3	Mid	1.19	4.55	45.5	0.3	45.2
Jul	1	Mid	1.19	4.56	45.6	0.3	45.4
Jul	2	Late	1.04	4	40	0.1	39.9
Jul	3	Late	0.6	2.46	27.1	0.1	27
Aug	1	Late	0.35	1.51	1.5	0	1.5
Total crop water requirement					**280**	**10.4**	**272**

From Table 5.5, the total crop water requirement for maize, if planted in May, is 280 mm and the irrigation requirement is 272 mm after subtracting the effective rainfall of 10.4 mm.

BVIS has fluvisols with a water holding capacity of 180 mm m^{-1} (DoI 2015). Using this water holding capacity as the soil water (SW) soon after rice harvest and the recorded irrigation water (488 mm) applied by farmers in winter irrigation during the experiment, graph of time in days vs water in mm was plotted. Figure 5.1 below shows the status of water applied by farmers against SW and what the crop requires for the whole season.

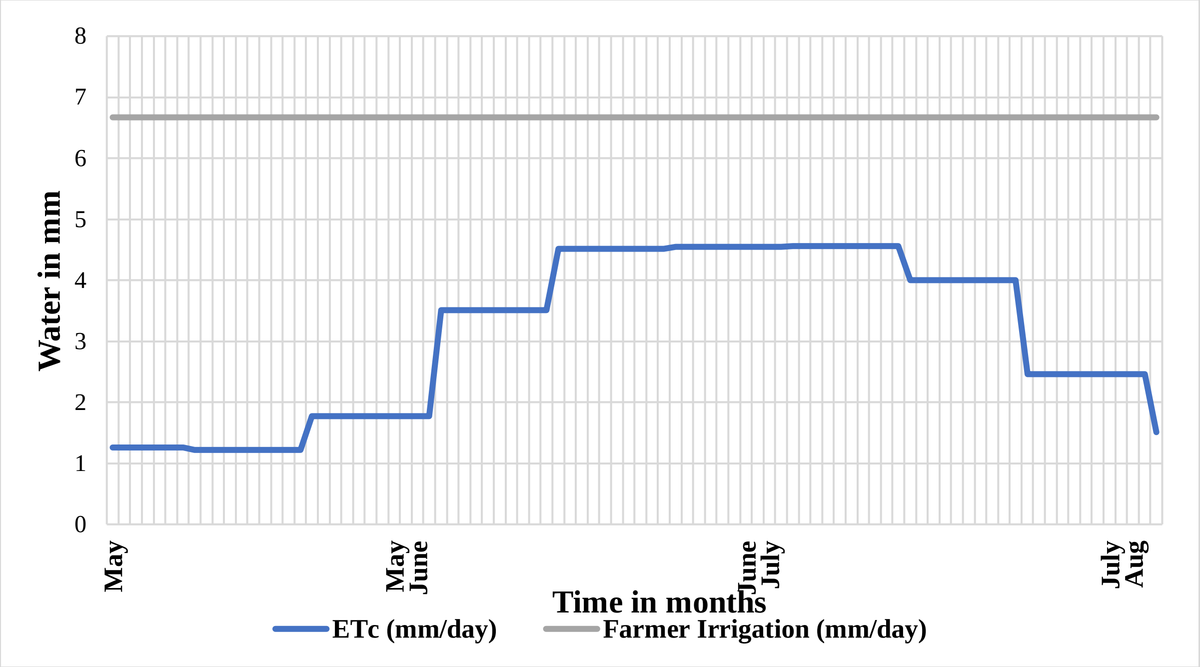


Figure 5. 1: Showing Farmer Irrigation against crop water requirement (May to August).

Figure 5.2 below shows depletion of stored SW as the crop grows as predicted by Cropwat. As maize grows, crop water use (CWU) increases while the SW gets less and less from May to August.

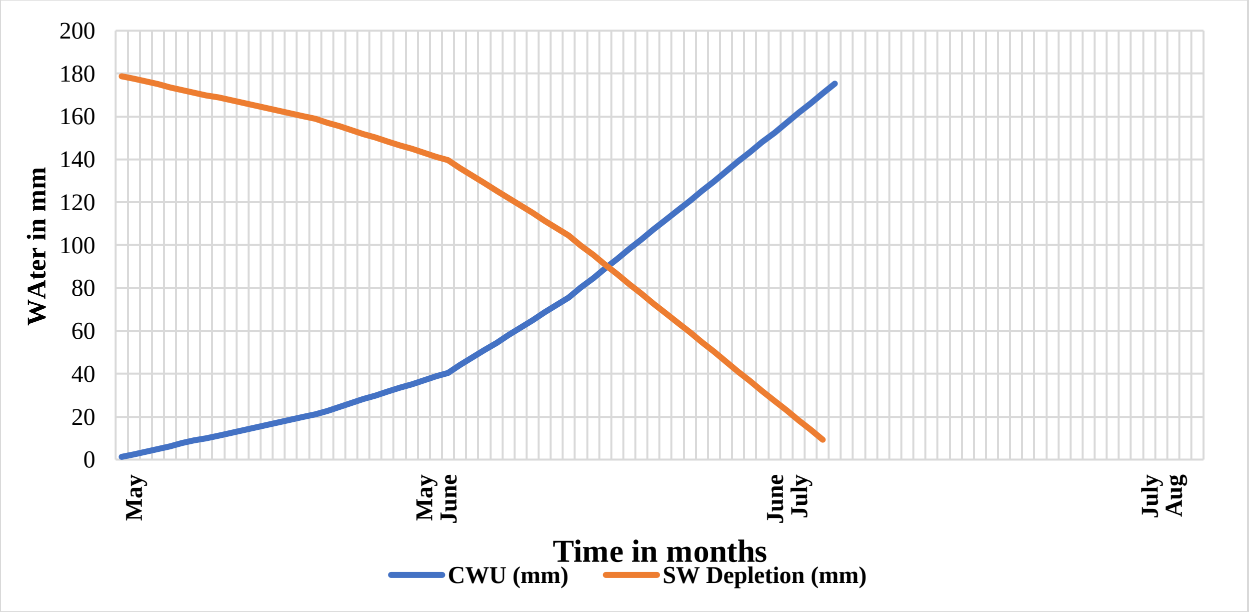


Figure 5. 2: CWU and SW from May to August

Figure 5.2 shows that SW will be depleted in 60 days after planting which is due to increased crop water demand as the crop grows and assuming that there is no rainfall and a rooting depth of 1 m. This indicates that the utilization of residual soil water in BVIS should be supplemented with irrigation 60 days after crops are planted in May. This is viable because the river runs out of water from mid-September onwards. As highlighted earlier on, rice in BVIS is harvested in April and the soil profile takes 14 days to drain before it is used for another cropping.

Table 5.6 shows ETc based on Cropwat for BVIS when maize is planted in August. It also shows different growth stages (initial (Init), development (Dev), mid and late growth stages).

Table 5. 6: ETc for maize in BVIS from August to November.

Month	Decade (10 days)	Stage	Kc coeff	ETc mm/day	ETc mm/dec	Eff rain mm/dec	Irr. Req. mm/dec
Aug	1	Init	0.3	1.3	9.1	0.1	9
Aug	2	Init	0.3	1.37	13.7	0.1	13.5
Aug	3	Dev	0.45	2.16	23.8	0.1	23.7
Sep	1	Dev	0.91	4.64	46.4	0.1	46.3
Sep	2	Mid	1.19	6.44	64.4	0	64.4
Sep	3	Mid	1.2	6.81	68.1	0.4	67.7
Oct	1	Mid	1.2	7.22	72.2	0.6	71.7
Oct	2	Late	1.1	6.63	66.3	0.8	65.5
Oct	3	Late	0.6	3.76	41.3	5	36.3
Nov	1	Late	0.35	2.14	2.1	0.7	2.1
Total crop water requirement					**407**	**7.9**	**400**

From Table 5.6, the total CWR for maize if planted August is 407 mm and the irrigation requirement (IR) is 400 mm after subtracting the effective rainfall of 7.9 mm. All this is under assumed furrow irrigated maize cropping. It should be noted that the IR is much higher with later planting than early planting because of higher seasonal ETo (caused by warmer temperatures) and drier soil profile (caused by drainage and consumption by weeds) conditions available at the time of later planting, which is 60 days after rive harvest. Rice is harvested from early to end April depending on the date of planting and arrival of summer rains.

Later planting, the extra 180 mm needs to be applied before planting because residual soil water will have drained out of soil profile or used by weeds. Hence, using this extra 180 mm as SW available at the time of later planting after rice harvest and the recorded irrigation water (488 mm) applied by farmers in winter irrigation, graph of time in days vs water in mm was plotted. Figure 5.3 shows the status of water applied by farmers against SW and what the crop requires for the whole season from August to November.

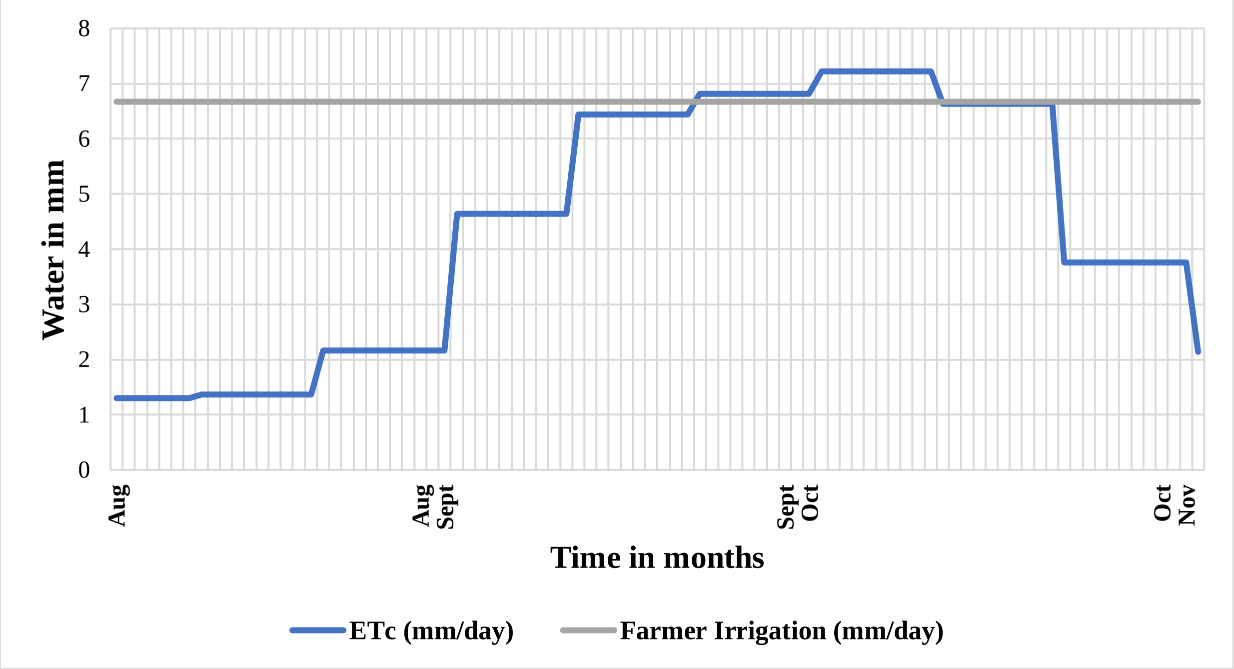


Figure 5. 3: Showing Farmer Irrigation against CWR August to November.

Figure 5.4 shows depletion of SW as the crop grows. As maize grows, CWU increases while the SW gets less and less from August to November.

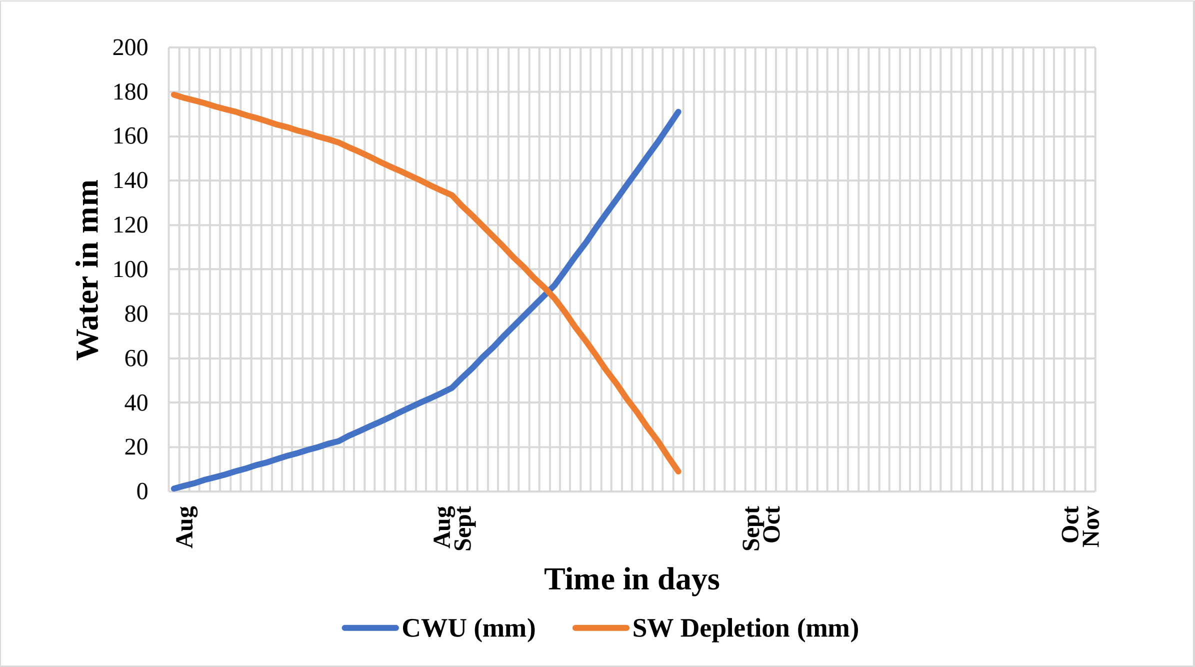


Figure 5. 4: CWU and SW from August to November

Figure 5.4 shows that SW will be depleted 49 days after planting as the crop water demand increases and assuming that there is no irrigation or rainfall. The extra 180 mm applied before late planting will be depleted by the end of September which is unfortunately the time when the river runs out of water. This clearly shows that residual soil water utilization with late planting is not a viable option for BVIS.

5.4 Results and discussion

From ANOVA, it is shown that there is a significant difference between farmer irrigation (and farmers did not irrigate every 21 days because the river ran dry) and irrigation based on soil water monitoring tools. Standard error also shows that the mean was estimated with good precision. On average BVIS farmers apply 488 mm of water including the initial soil profile wetting. Under this experiment, emulated conditions of wet soil profile soon after rice harvest were created by wetting the soil profile with 180 mm of irrigation. This was used as the residual soil water available after rice harvest.

Below is a demonstration that if farmers in BVIS plant soon after rice harvest they would be able to cultivate a bigger area by carefully utilizing the residual soil water, rather than waiting until fields dry up, unless field is too wet to plant.

5.4.1 Potential irrigation area under early planting (May to August)

If farmers plant soon after rice harvest, maize will need about 272 mm of irrigation which is ETc minus effective rainfall (Eff rain). SW is 180 mm and Farmer Irrigation is 488 mm. Farmer plot size is 900 m^2 and there are 1777 farmers (1611 irrigating). Water which could be saved through utilization of SW per farmer holding 900 m^2 plot size would be;

- Saved water (mm) = FI + ASW – IR (ETc-Eff rain)
  = (488 + 180 – 272) mm = 396 mm
- Saved water in m^3 = (396 mm / 1000 mm) m * 900 m^2 = 356.4 m^3

Area which could be irrigated using this saved water;

- Irrigation area = Saved water (m^3) / IR
  = 356.4 m^3 / 0.272 m = 1310.3 m^2

Irrigation area in hectares (ha) will be; 1310.3 m^2 / 10000 m^2 = 0.13 ha. This means that each BVIS farmer would irrigate 0.13 ha more in addition to the usual allocated 0.09 ha by utilizing the residual soil water through early planting and if scheduled correctly. For 1611 BVIS farmers, 209 ha (0.13 ha * 1611) would be irrigated in addition to the designated 145 ha. This means that there is a possibility of irrigating 354 ha (145 ha + 209 ha) in BVIS through utilization of residual soil water.

5.4.2 Potential irrigation area under late planting (August to November)

If farmers plant soon after rice harvest, maize will need an IR of 400 mm which is ETc minus Eff rain. SW is 180 mm (assumed extra application before planting because the soil profile will have dried up at this point as indicated earlier on in this chapter) and Farmer Irrigation is 488 mm. Farmer plot size is 900 m^2 and there are 1777 farmers (1611 irrigating). Water which could be saved through utilization of SW per farmer 900 m^2 plot size would be;

- Saved water (mm) = FI + ASW – IR (ETc-Eff rain)

  = (488 + 180 – 400) mm = 268 mm
- Saved water in m^3 = (268 mm / 1000 mm) m * 900 m^2 = 241.2 m^3

Area which could be irrigated using this saved water;

- Irrigation area = Saved water (m^3) / IR
  = 241.2 m^3 / 0.4 m = 603 m^2

Irrigation area in hectares (ha) will be; 603 m^2 / 10000 m^2 = 0.06 ha. This means that each BVIS farmer would irrigate 0.06 ha more in addition to the usual allocated 0.09 ha by utilizing the residual soil water through late planting. For 1611 BVIS farmers, 96 ha (0.06 ha * 1611) would be irrigated in addition to the designed 145 ha. This means that there is a possibility of irrigating 241 ha (145 ha + 96 ha) in BVIS through utilization of residual soil water.

From calculations on planting dates above (May to August and August to November), it shows that farmers would be able to irrigate more when they plant in May (354 ha) than when they plant in August (241 ha) through careful utilization of residual soil water. This is because maize will need more water in August to November due to higher crop evapotranspiration than in May to August and also because later planting starts off with a drier soil profile. The months of May, June and July are cooler than August, October and November hence lower ETc values. Utilization of residual soil water and cooler conditions through early planting would indeed result in expansion of the irrigated area for BVIS. Residual soil water utilization would work best if there is some certainty that additional water would be available whenever the need arises during the cropping period. It is very evident that this approach would not work with late planting for Bwanje Valley Irrigation Scheme because the scheme runs out of water from September to December and that the soil profile will be drier (caused by drainage and consumption by weeds). Current construction of the dam upstream of the Namikokwe River is good news for this approach but still, drier soil profile available at the time means higher irrigation requirement.

Based on the Chameleon patterns shown in this experiment, chances are high that the residual soil water is more than what has been calculated in this chapter. Hence, with actual measurement, the scheme would be able to irrigate more than 354 ha.

It must be noted that this is a computer desktop analysis (with assumed parameters) just to give an idea of what could happen to the irrigated area if farmers planted soon after rice harvest to utilize residual soil water, and if their irrigations were managed more judiciously. Chances are very high that these results might not be practical on the ground but close. Therefore, there is a need for another trial with actual early planting, soon after rice harvest and a later planting with a different calculation other than 488 mm regardless of whether starting on a wet or drier profile for BVIS. Field results from that trial should be compared with Climwat and Cropwat results presented in this chapter to see how realistic careful residual soil water utilization is to expand the irrigated area for the scheme.

General Discussion

Bwanje Valley Irrigation Scheme is a farmer managed scheme. Water and land allocation, infrastructure operation and maintenance are done by farmers themselves through an organization called the Water Users Group. Extension and technical services are provided by the Malawian Government through the Departments of Irrigation and of Agricultural Extension Services.

Periodically, government officers stationed at the District Council and Extension Planning Area Offices supervise the scheme. This is the same for all other smallholder irrigation schemes in the country. Bwanje Valley Irrigation Scheme and other smallholder irrigation schemes in Malawi face shortages of water supply, poor irrigation water management, low yields and low areas under irrigation during the winter season. These problems are caused by a lack of soil water monitoring tools, low soil fertility, poor operation and maintenance of scheme infrastructure, lack of ownership within the farmers, insufficient level of education prevailing in these farmers and insufficient storage.

With this research, the effect of applying more nutrients than what farmers apply and managing them with Wetting Front Detectors on maize yield was tested. The impact of using Chameleon Sensors to manage soil water when scheduling irrigation on maize yields was also tested. The possibility of expanding the irrigated area in winter through careful utilization of residual soil water after rice harvest was also explored through a desktop analysis. All this was done to find the best way to irrigate in order to expand the area under irrigation and improve maize yield for Bwanje Valley Irrigation Scheme, which would also apply to other smallholder irrigation schemes in Malawi.

It has been shown in chapters 3 and 4, that effective use of nutrients and irrigation water has an impact on yield of maize in Bwanje Valley Irrigation Scheme. Chapter 5 also demonstrated that careful utilization of residual soil water available after rice harvest can expand the area under irrigation in Bwanje Valley Irrigation Scheme. This could be done by early planting, soon after rice harvest. Maize yield and seasonal irrigation water applied to crops were subjected to ANOVA and results show that there were highly significant differences among treatments. Uniform soil conditions in all treatments rendered blocking unnecessary, as there were no significant differences among three blocks. ANOVA also showed that yield and irrigation water results for this trial are scientifically acceptable and were estimated with high precision because CV was less than 25% and SE was low.

Water and maize yield data was subjected to a computer SAS analysis and the results show that OILN and SILN received the same amount of water but significantly less than FIFN and FILN during the season. With yields, it was shown that OILN was significantly higher than SILN, FILN and FIFN.

This research has revealed that low maize yields in Bwanje Valley Irrigation Scheme are caused by low soil fertility and poor nutrient management. Under the same irrigation conditions, luxury nutrients yielded more (4.7 t ha^{-1}) than farmer nutrients (3.4 t ha^{-1}). This clearly shows that farmers in Bwanje do not apply enough nitrogen, phosphate and potassium to obtain maximum yields for maize or they leach much of the N out of the profile. Low soil fertility was confirmed by soil tests carried out prior to the trial. Results indicated low nitrogen and potassium. It has also been noted that with the same water and nutrients applied, SILN (4.3 t ha^{-1}) yielded very much lower than OILN (5.75 t ha^{-1}). Closer examination of Chameleon colour patterns, canopy cover and crop height data show minor variations between the two treatments. It is, therefore, very difficult to identify the real cause of the difference in yield. The only suspected cause is water interference from bordering farmers' plots and an unlined tertiary canal. Site specific soil tests need to be done in smallholder irrigation schemes prior to the cropping season to determine soil fertility. This should determine the best nutrient regime to be applied by farmers. One size fit all will not help to improve maize yields in smallholder farms which in turn will not uplift their livelihoods.

Low soil fertility in smallholder irrigation or rain-fed farms is also caused by nutrient mining which occurs through the general practice of burning crop residues after harvest, and by applying less than the crops take up. Burning residues will increase the need for chemical fertilizers, which will definitely increase the cost of production to farmers. Farmers should be encouraged to plough back crop residues after harvest. This will improve soil chemical and physical properties and in turn reduce production costs and improve maize yields.

The initiative taken by the Government of Malawi to phase out NPK (23:21:0+4s) fertilizer which has zero potassium and replacing it with NPK (23:10:5+6S+1.0Zn) is a positive step towards improving maize yields in both irrigated and rainfed agriculture. In its communication Ref. No.: 30/15/4 dated 2nd January, 2016, the Ministry of Agriculture, Irrigation and Water Development says the change is necessary because NPK (23:10:5+6S+1.0Zn.) has potassium and zinc which are essential nutrients for maize productivity.

When luxury nutrients were managed by Wetting Front Detectors and water managed by Chameleon Sensors, yields were almost doubled, from 3.4 t ha^{-1} under farmer irrigation to 5.75 t ha^{-1} under optimum irrigation. Use of Wetting Front Detectors to manage nutrients ensured that nutrients remained within the plant root zone and hence were fully utilized. Chameleon Sensors ensured that crops were given optimum amounts of water which prevented plant water stress and over irrigation. Combined use of Wetting Front Detectors and Chameleon Sensors increased maize yields by reducing nitrate leaching and by preventing under irrigation.

In general, smallholder irrigation schemes in Malawi need to prioritize management of nutrients and water by acquiring and using Wetting Front Detectors and Chameleon Sensors. These soil water and nutrient monitoring tools will prevent or reduce over irrigation and increase maize yields. Many smallholder irrigation schemes in Malawi lack these soil water and nutrient monitoring tools which could be largely due to insufficient capital input. Wetting Front Detectors and Chameleon Sensors are cheap, easy to use and operate. Having said this, emphasis should be made to make sure that small-scale irrigation farmers acquire these tools. This could be done through farmer contributions, and through sustainable government and donor aid programs.

On the other hand, over and under irrigation is also caused by poor maintenance and operation of irrigation infrastructure. Broken or damaged gate valves affect control and delivery of water to crops. In Bwanje Valley Irrigation Scheme, there are cases whereby water ends up in unintended plots at night when no one is irrigating because of damaged gates and canals. This was witnessed during the trial. Therefore, maintenance of structures in smallholder irrigation schemes is crucial if over irrigation is to be reduced. Water User Groups need to carry out regular maintenance and repair scheme hydraulic structures where necessary. This can be achieved by developing an inventory of scheme’s infrastructure, carrying out routine inspections, developing maintenance plans and records, and having responsible subcommittees in place. This should be done with the help and consultation of Agricultural Extension Development Officers and Irrigation Officers.

Bwanje Valley Irrigation Scheme and other smallholder irrigation schemes in Malawi experience shortage of water towards the end of the winter irrigation season. Water sources to schemes dry up as temperatures become warmer. For example, discharge volume of Namikokwe River, which is the sole source of water to Bwanje Valley Irrigation Scheme declines markedly in the months of August, September, October and November. This could be partly caused by climate change and catchment degradation. This affects maize productivity. Solutions to this problem could be; (i) management and conservation of river catchments i.e. prevention of deforestation, forestation, avoiding river bank cultivation (ii) construction of in scheme water storage reservoirs, (iii) use of early maturing and drought resistant crop varieties and (iv) early planting. A dam which is being constructed upstream in the Namikokwe River will help reduce the water shortage problem faced by Bwanje Valley Irrigation Scheme during warmer periods. This should be applied to all smallholder irrigation schemes facing similar problems.

Introduction of Wetting Front Detectors and Chameleon Sensors to small-scale irrigation farmers should be done together with community sensitization and awareness meetings. Farmers should also be oriented and trained on how to use, operate and maintain these tools. These will induce a sense of ownership with farmers, which will ensure sustainability of the intervention. Without this approach, there is a high probability that these tools will be vandalized and stolen. This was one of the major problems faced during the trial period. Several sets of Chameleon Sensors were stolen during data collection and soon after termination of the trial. It is also thought that disguising the visibility of installed Chameleon Sensors in the field by covering them with a black box could reduce theft and vandalism.

Through a gross margin analysis done in chapter 3, it is very clear that Bwanje Valley Irrigation Scheme farmers would benefit if they apply more nitrogen and phosphorous to their maize than what they are currently doing. BVIS farmers should also include potassium in their nutrient regime because under this experiment it has been clearly shown that potassium is a limiting factor to their maize production. Though pH is not the main issue now, still BVIS farmers should start applying agricultural lime to their plots because soon or later it will become a problem because of poor irrigation water management prevailing in the scheme now. Luxury nutrients produced a profit of \$524 ha^{-1} while farmer nutrients produced \$201 ha^{-1}. Based on these calculations, it is worthwhile encouraging farmers to apply more nutrients than what they are currently applying.

Bwanje Valley Irrigation Scheme farmers should be encouraged to plant soon after rice is harvested so that they take advantage of available residual soil water. This would reduce the irrigation requirement and enable expansion of area under irrigation. In chapter 4, through a desk top analysis using Cropwat and Climwat, it was shown that Bwanje Valley Irrigation Scheme would be able to expand irrigated area to 354 ha, which is 209 ha more than is currently irrigated. This will, of course, with proper nutrient and water management, increase the scheme’s maize productivity and irrigated area. Early planting would also reduce the risk of running out of irrigation water within the cropping season. This should be applied to all other small-scale irrigation schemes with similar conditions to Bwanje Valley Irrigation Scheme.

Conclusion and recommendations

Low maize yields in Bwanje Valley Irrigation Scheme are caused by insufficient nutrients applied by farmers and poor irrigation water management. Poor irrigation water management is caused by lack of soil water monitoring tools in smallholder irrigation schemes like Bwanje. Farmers schedule their irrigation water based on local knowledge and experience. Soils in Bwanje Valley Irrigation Scheme have low nitrogen, phosphorus, potassium and pH which affect maize production. Burning of crop residues after harvest also mines nutrients from the soil and should be discouraged and contributes to global warming through GHGs emissions. Based on the results of this research, additional nutrient supply increases maize yield, and nutrient levels currently applied by the farmers are insufficient to obtain maximum yields of maize in Bwanje Valley Irrigation Scheme.

Maximum maize yields in Bwanje Valley Irrigation Scheme can be obtained when nutrients and water are managed by Wetting Front Detectors and Chameleon Sensors. Wetting Front Detectors help to identify leaching of nitrates and Chameleon Sensors enables the irrigator to avoid over and under irrigation. In the absence of WFDs farmers can minimize nitrate losses through leaching by the split application of N. Wetting Front Detectors and Chameleon Sensors are easy to use, operate and manage, hence they are suitable for Bwanje Valley Irrigation Scheme and other small-scale irrigation schemes farmers with a low level of education and income.

Economically, it is profitable to increase nutrient supply over levels farmers currently supply for maize production in Bwanje Valley Irrigation Scheme. Farmers can double their income and produce if they improve nutrient supply and use soil and water monitoring tools.

Residual soil water can be carefully utilized by early planting which is soon after rice harvest. Based on Cropwat and Climwat simulations, Bwanje Valley Irrigation Scheme can cultivate 209 ha more in addition to the designed 145 ha. It must be noted that these results are based on computer programs which might not be exact and practical. Therefore, further research should be carried out by having trials done soon after rice harvest and be compared to this computer output. In that research, it should also be established as to why farmers do not plant maize soon after rice harvest. It is also clear from this trial that deeper soil layers in Bwanje

Valley Irrigation Scheme remain wet for almost the whole winter. Other deeper-rooted crops apart from maize should be tested so that this soil water is utilized. Further research is also required to find the causes of variations in maize yield whilst grown under similar agronomic factors and conditions, which was experienced but not understood in this trial.

Appendices

Appendix A: Averaged plant canopy cover measurements for maize in BVIS

Averaged measurements for each treatment from three blocks

Time	Plant Canopy Cover (%)			
Days	FIFN	FILN	OILN	SILN
1	0	0	0	0
18	2.4	3.6	3	2.1
28	7.4	8.9	13.8	11.9
35	20.5	24.9	25.3	22.9
42	32	32	37.1	34
53	55.6	64.8	71.1	66.6
59	58	72.4	76.1	74.6
67	67.4	81.1	86.6	79.8
74	70.7	84.7	93.4	81.5
81	72.7	87.2	96.9	82.7
88	73.3	87.5	98	83.3
95	71.2	86.3	97.2	82.9
102	70.1	85.1	95.7	81.6

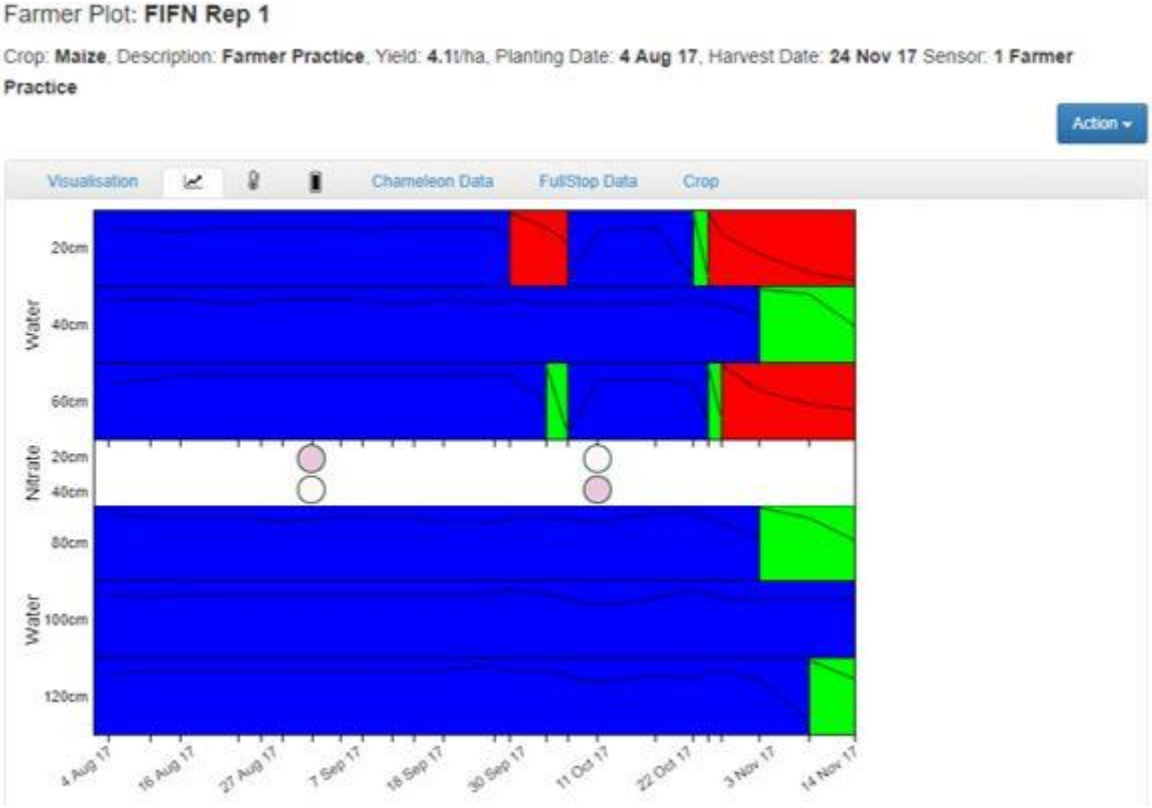
Appendix B: Averaged plant height measurements for maize in BVIS

Averaged measurements for each treatment from three blocks

Time	**Plant Height (cm)**			
Days	**FIFN**	**FILN**	**OILN**	**SILN**
1	0	0	0	0
18	6.5	6.7	6.8	6.5
28	9.3	10.7	13.7	12.1
35	17.6	18.9	20.4	19.7
42	31.3	37.3	39.4	37.5
53	59.5	73.6	73.5	74.2
59	141.1	152.8	154.2	152.3
67	150.1	169.5	170.9	169.8
74	153.7	172.7	176.5	172.4
81	160.6	177.9	183.2	178.4
88	160.9	178.6	183.7	178.9
95	160.9	178.6	183.7	178.9
102	160.9	178.6	183.7	178.9

Appendix C: Chameleon colour patterns for FIFN Rep 1

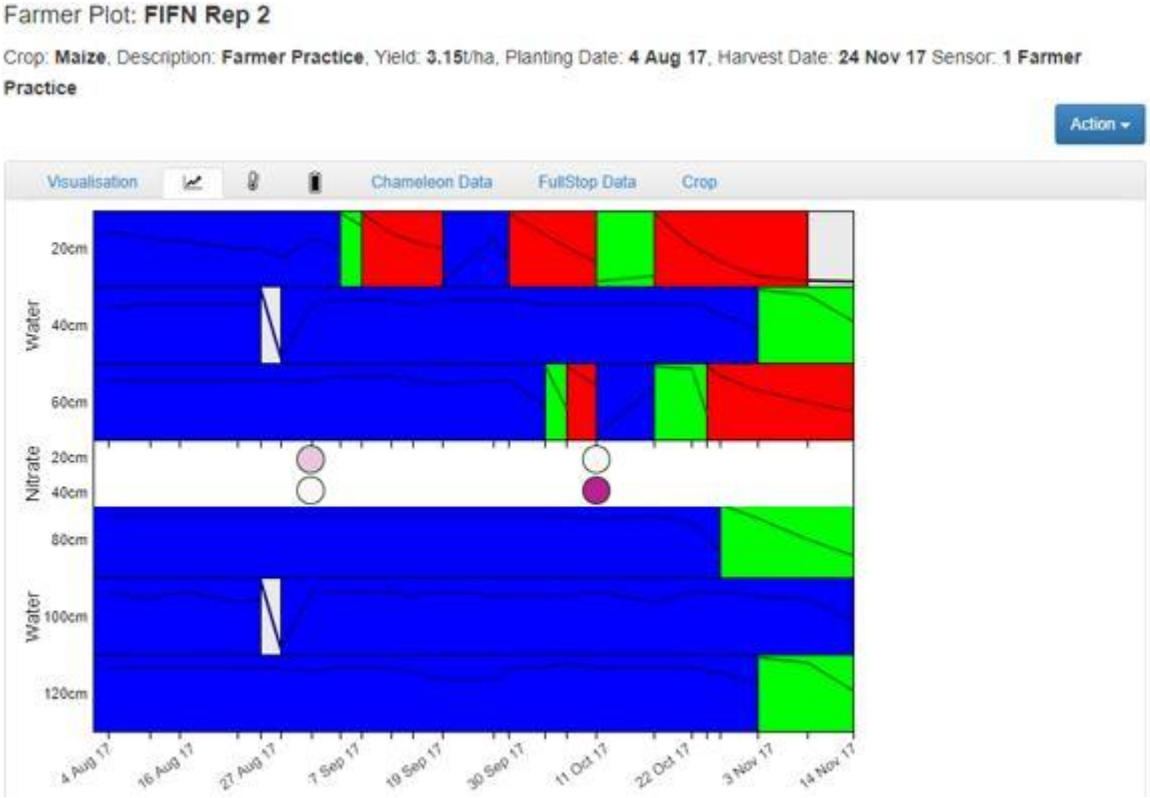
These patterns show soil water status up to 120 cm depth, nitrates and yields for maize obtained during the trial



Farmer Plot: **FIFN Rep 1**

Crop: **Maize**, Description: **Farmer Practice**, Yield: **4.1t/ha**, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17** Sensor: **1 Farmer Practice**

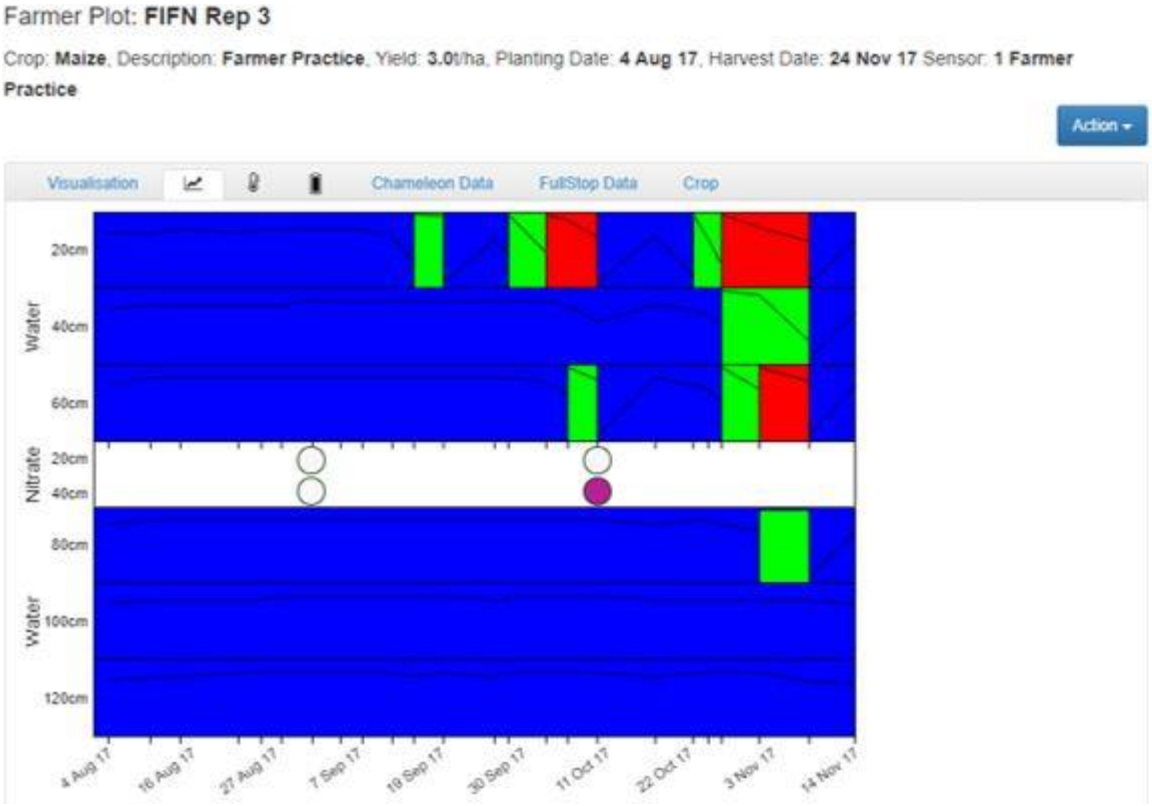
Appendix D: Chameleon colour patterns for FIFN Rep 2



Farmer Plot: **FIFN Rep 2**

Crop: **Maize**, Description: **Farmer Practice**, Yield: **3.15**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17** Sensor: **1 Farmer Practice**

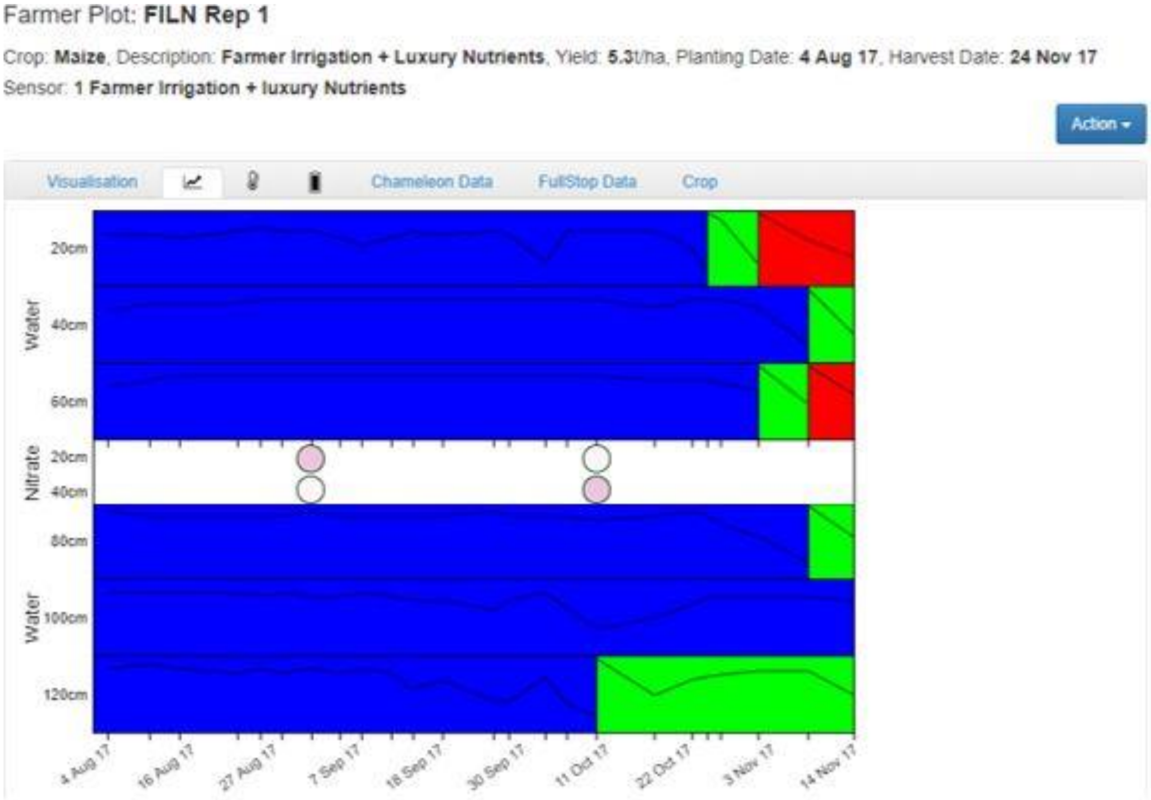
Appendix E: Chameleon colour patterns for FIFN Rep 3



Farmer Plot: **FIFN Rep 3**

Crop: **Maize**, Description: **Farmer Practice**, Yield: **3.0t/ha**, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17** Sensor: **1 Farmer Practice**

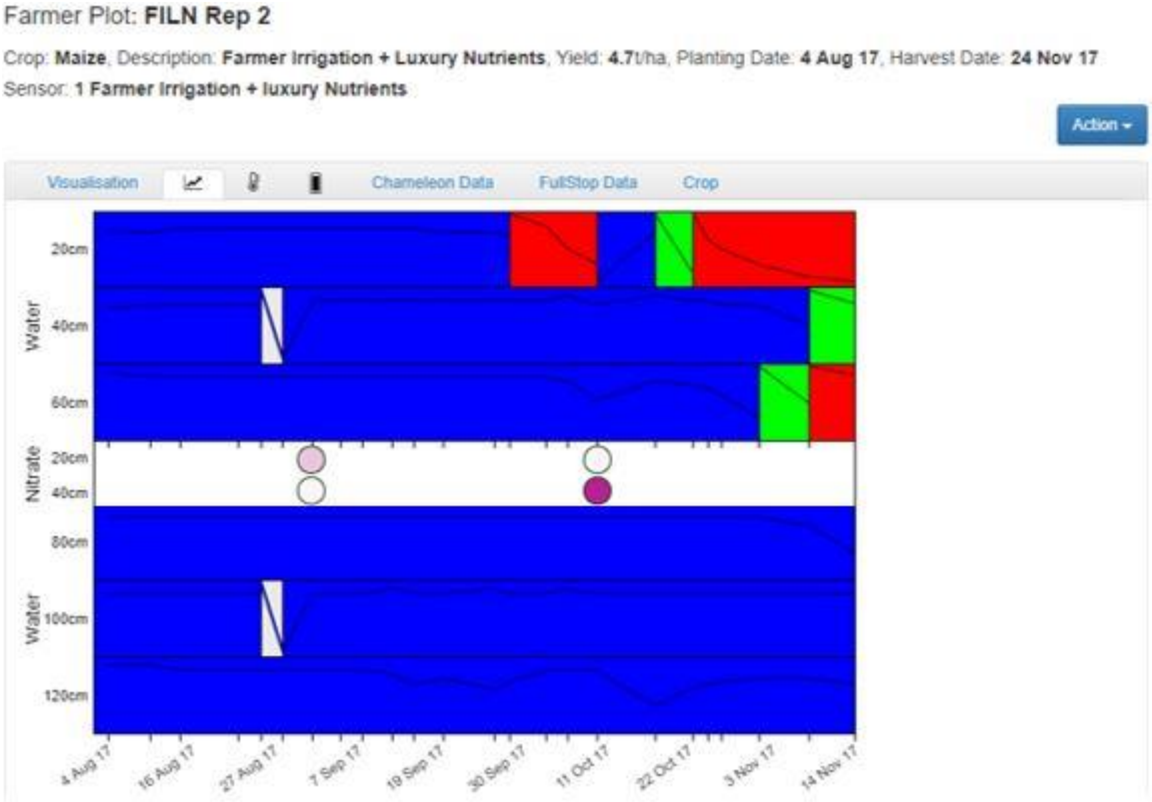
Appendix F: Chameleon colour patterns for FILN Rep 1



Farmer Plot: **FILN Rep 1**

Crop: **Maize**, Description: **Farmer Irrigation + Luxury Nutrients**, Yield: **5.3**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17**
Sensor: **1 Farmer Irrigation + luxury Nutrients**

Appendix G: Chameleon colour patterns for FILN Rep 2



Farmer Plot: **FILN Rep 2**

Crop: **Maize**, Description: **Farmer Irrigation + Luxury Nutrients**, Yield: **4.7**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17**

Sensor: **1 Farmer Irrigation + luxury Nutrients**

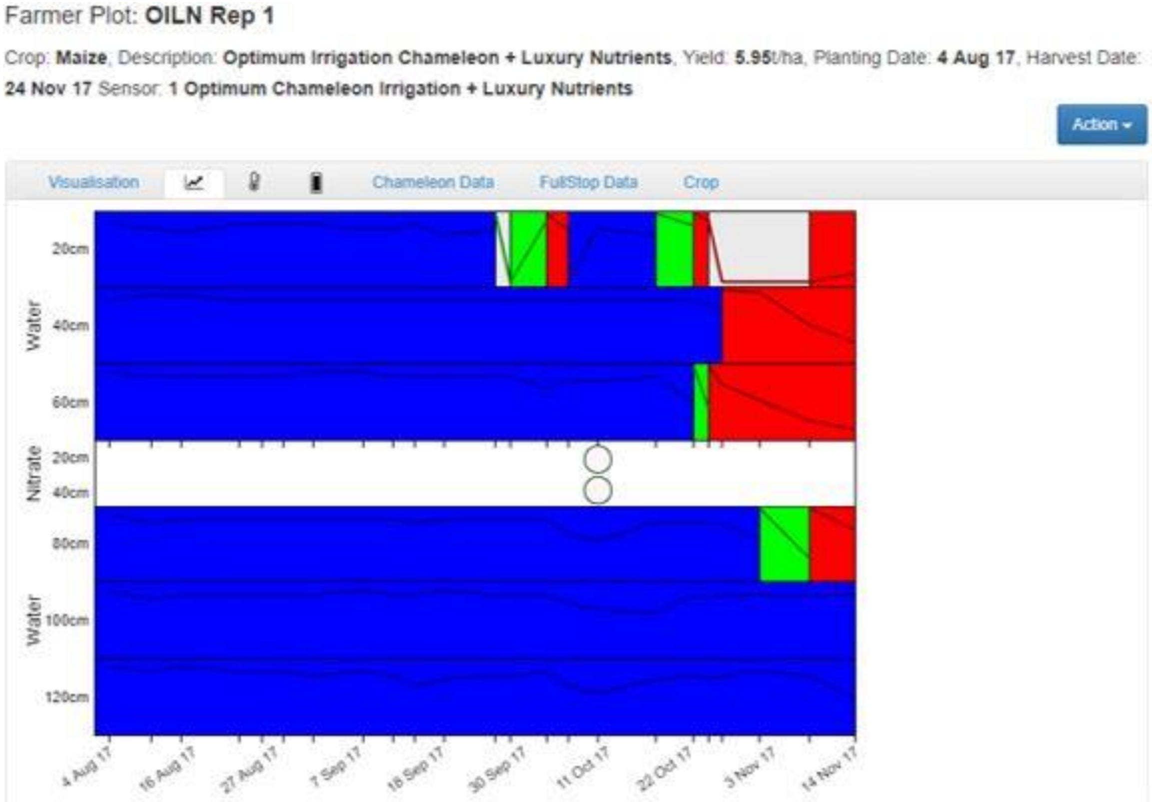
Appendix H: Chameleon colour patterns for FILN Rep 3

Farmer Plot: **FILN Rep 3**

Crop: **Maize**, Description: **Farmer Irrigation + Luxury Nutrients**, Yield: **4.15**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17**

Sensor: **1 Farmer Irrigation + luxury Nutrients**

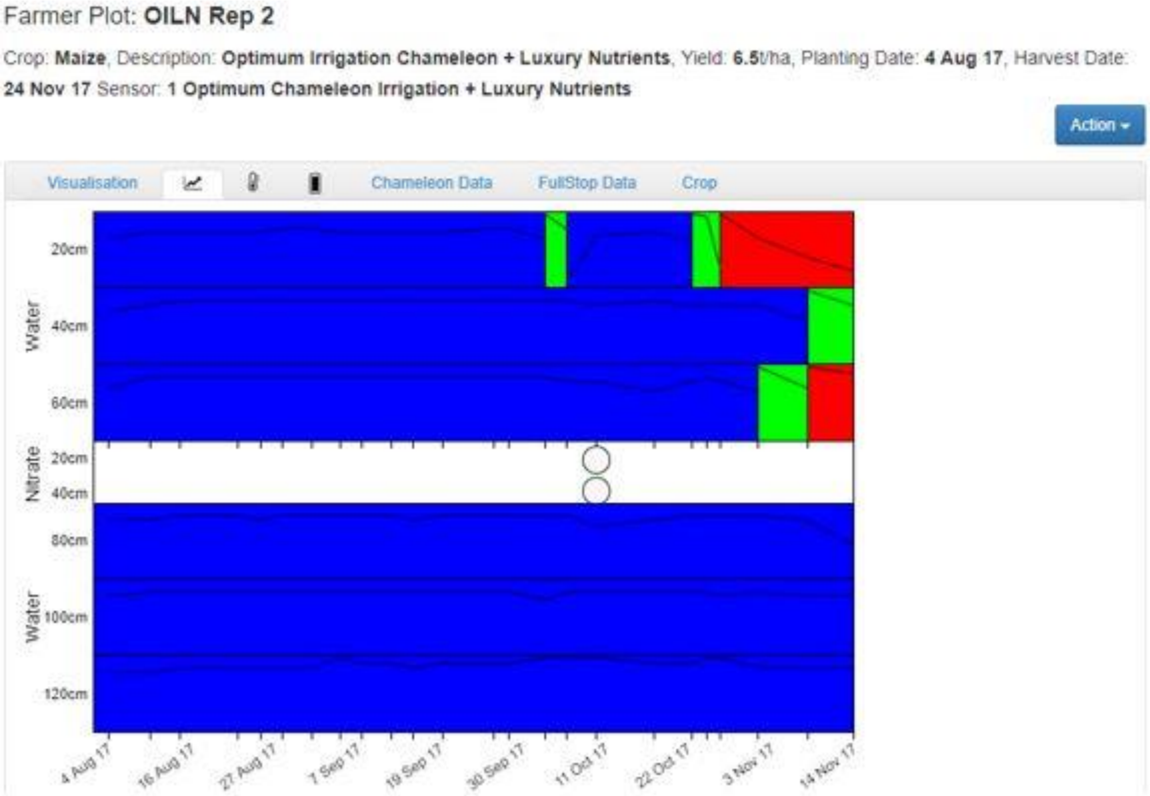
Appendix I: Chameleon colour patterns for OILN Rep 1



Farmer Plot: **OILN Rep 1**

Crop: **Maize**, Description: **Optimum Irrigation Chameleon + Luxury Nutrients**, Yield: **5.95**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17** Sensor: **1 Optimum Chameleon Irrigation + Luxury Nutrients**

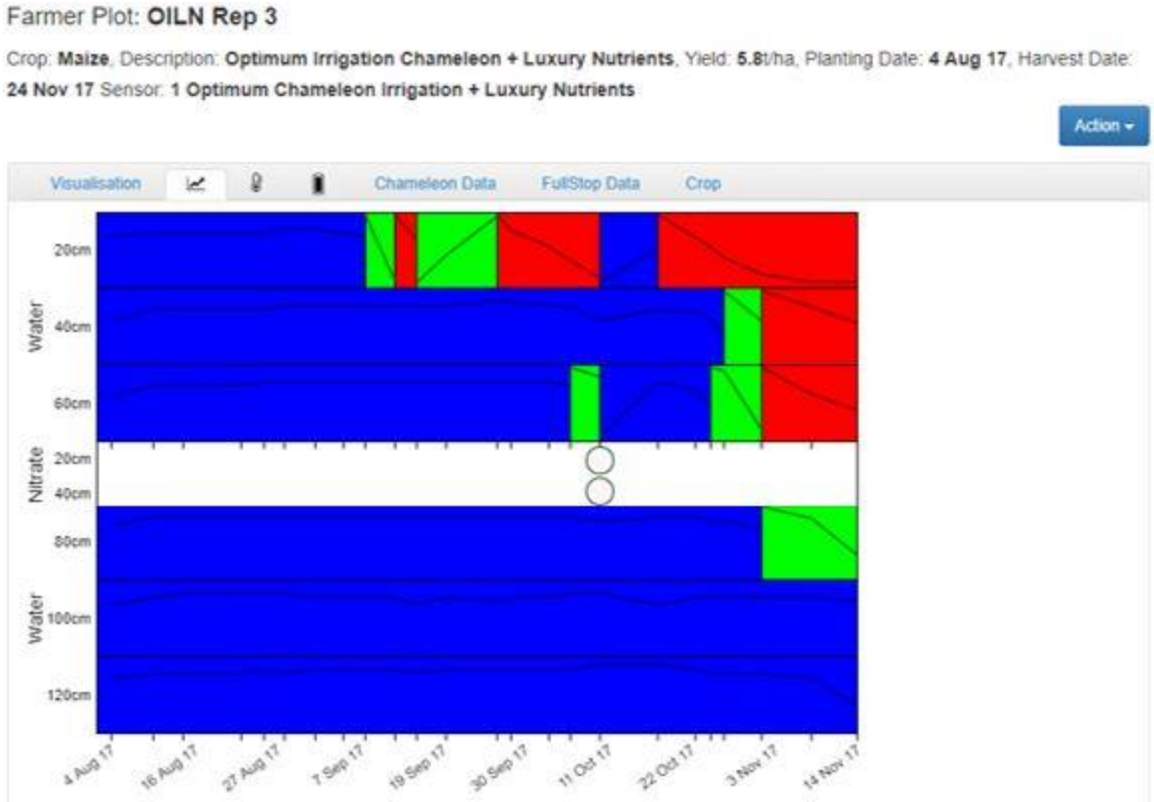
Appendix J: Chameleon colour patterns for OILN Rep 2



Farmer Plot: **OILN Rep 2**

Crop: **Maize**, Description: **Optimum Irrigation Chameleon + Luxury Nutrients**, Yield: **6.5**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17** Sensor: **1 Optimum Chameleon Irrigation + Luxury Nutrients**

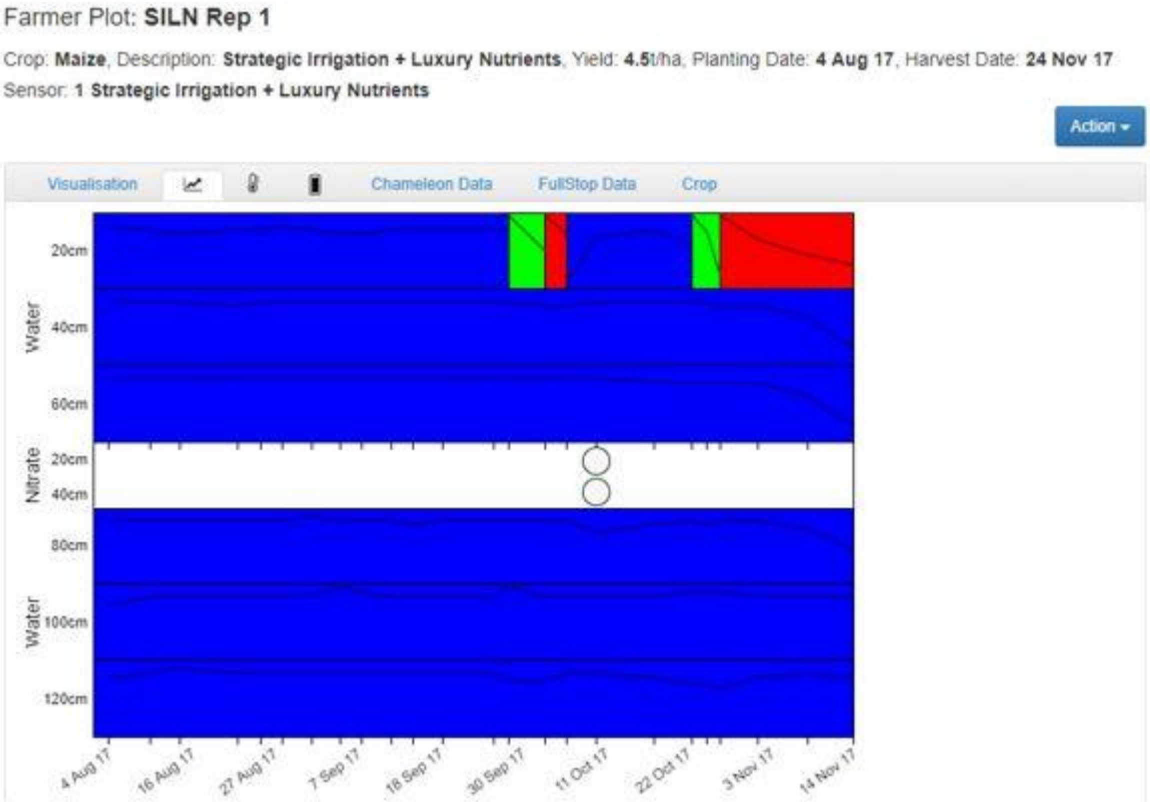
Appendix K: Chameleon colour patterns for OILN Rep 3



Farmer Plot: **OILN Rep 3**

Crop: **Maize**, Description: **Optimum Irrigation Chameleon + Luxury Nutrients**, Yield: **5.8**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17** Sensor: **1 Optimum Chameleon Irrigation + Luxury Nutrients**

Appendix L: Chameleon colour patterns for SILN Rep 1

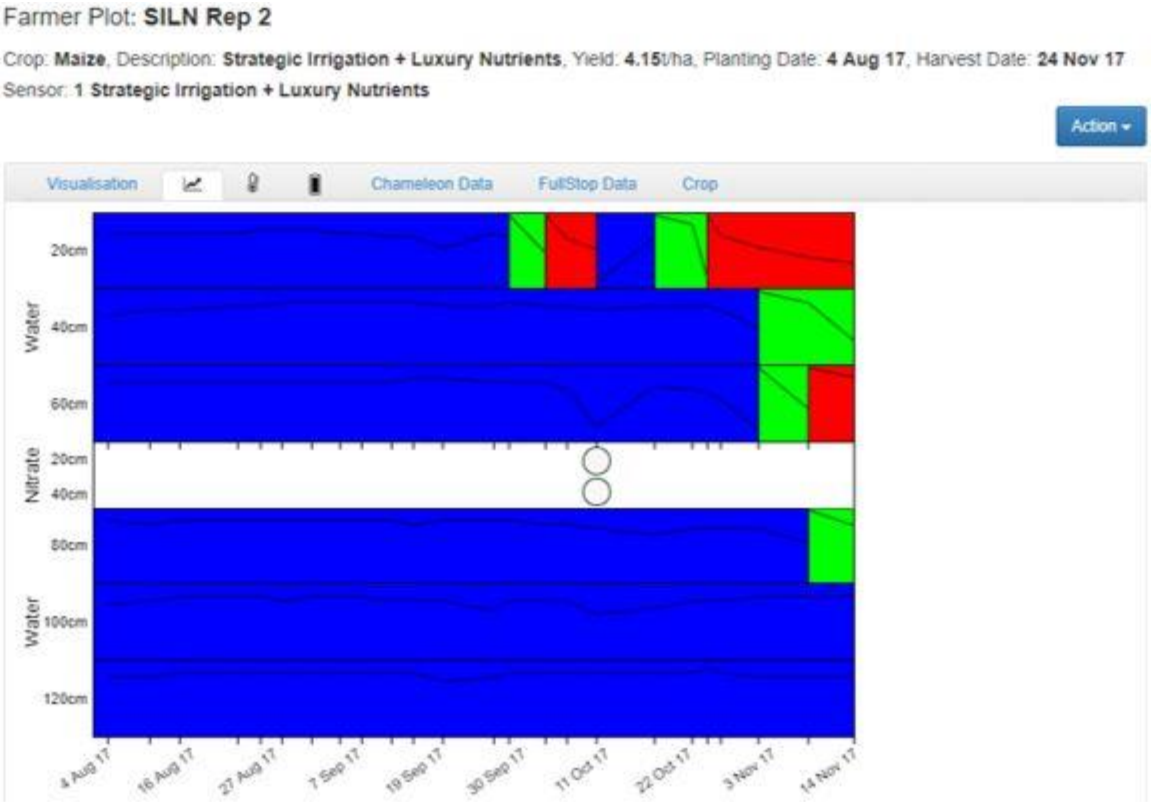


Farmer Plot: **SILN Rep 1**

Crop: **Maize**, Description: **Strategic Irrigation + Luxury Nutrients**, Yield: **4.5**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17**

Sensor: **1 Strategic Irrigation + Luxury Nutrients**

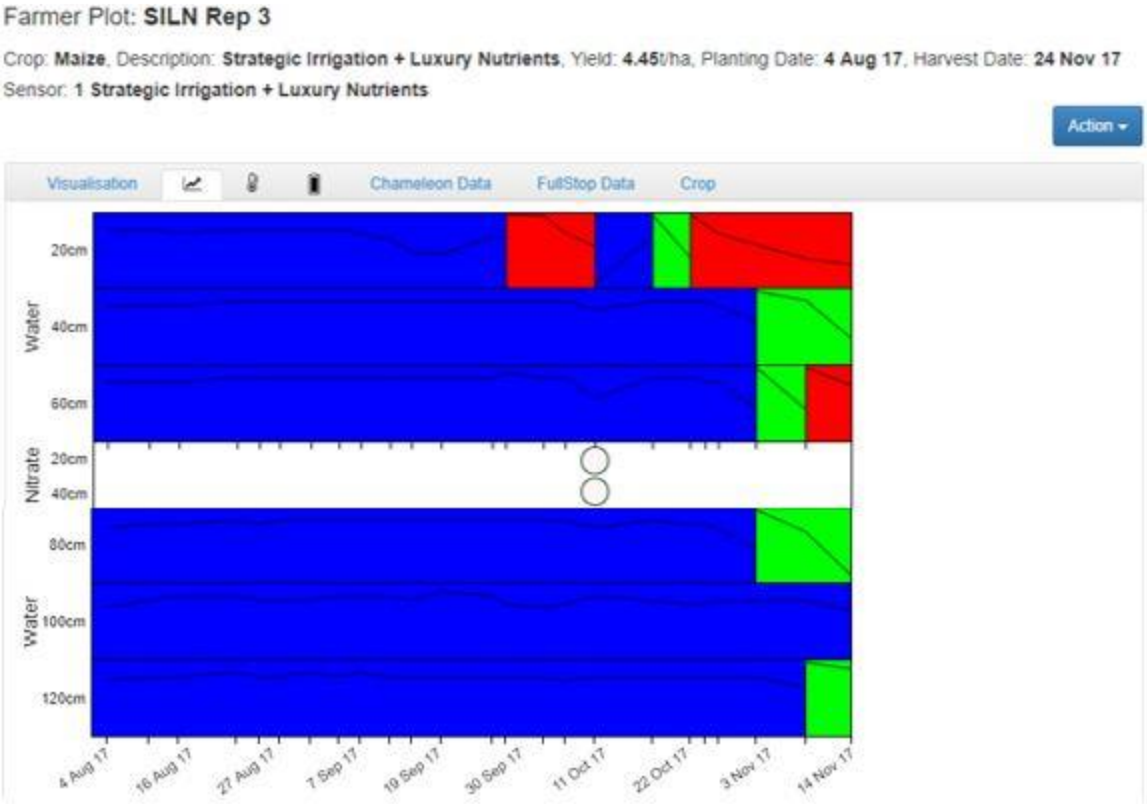
Appendix M: Chameleon colour patterns for SILN Rep 2



Farmer Plot: **SILN Rep 2**

Crop: **Maize**, Description: **Strategic Irrigation + Luxury Nutrients**, Yield: **4.15**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17**
Sensor: **1 Strategic Irrigation + Luxury Nutrients**

Appendix N: Chameleon colour patterns for SILN Rep 3



Farmer Plot: **SILN Rep 3**

Crop: **Maize**, Description: **Strategic Irrigation + Luxury Nutrients**, Yield: **4.45**t/ha, Planting Date: **4 Aug 17**, Harvest Date: **24 Nov 17**

Sensor: **1 Strategic Irrigation + Luxury Nutrients**

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